Leptogenesis and Fundamental Symmetries of Nature

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Baryon Number Asymmetry in SM

- Within the SM:
  - CP violation in quark sector not sufficient to explain the observed matter-antimatter asymmetry of the Universe
- CP phase in quark sector:

Shaposhnikov, 1986; Farrar, Shaposhnikov, 1993

$$B \simeq \frac{\alpha_w^4 T^3}{s} \delta_{CP} \simeq 10^{-8} \delta_{CP} \qquad \delta_{CP} \simeq \frac{A_{CP}}{T_C^{12}} \simeq 10^{-20}$$

  - effects of CP violation suppressed by small quark mixing

$$A_{CP} = (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2) \cdot J$$

$$\longrightarrow \quad B \sim 10^{-28}$$

too small to account for the observed

- Various Baryogenesis mechanisms (see Babu's talk)
- neutrino masses open up a new possibility

Fukugita, Yanagida, 1986

[For a review, see e.g. M.-C. C. TASI 2006 Lectures on Leptogenesis, hep-ph/0703087]

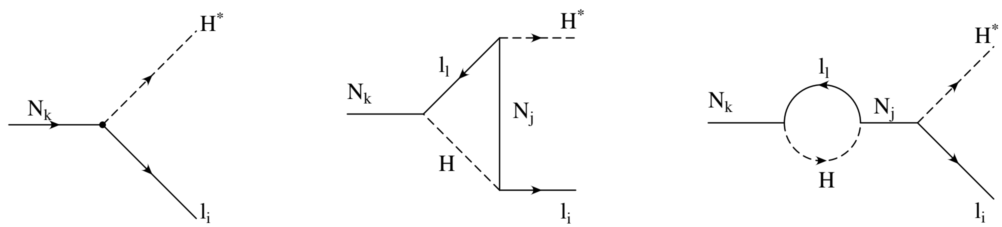
Leptogenesis

Leptogenesis

Fukugita, Yanagida, 1986

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

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



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

- sphaleron process convert ΔL → ΔB
- the asymmetry

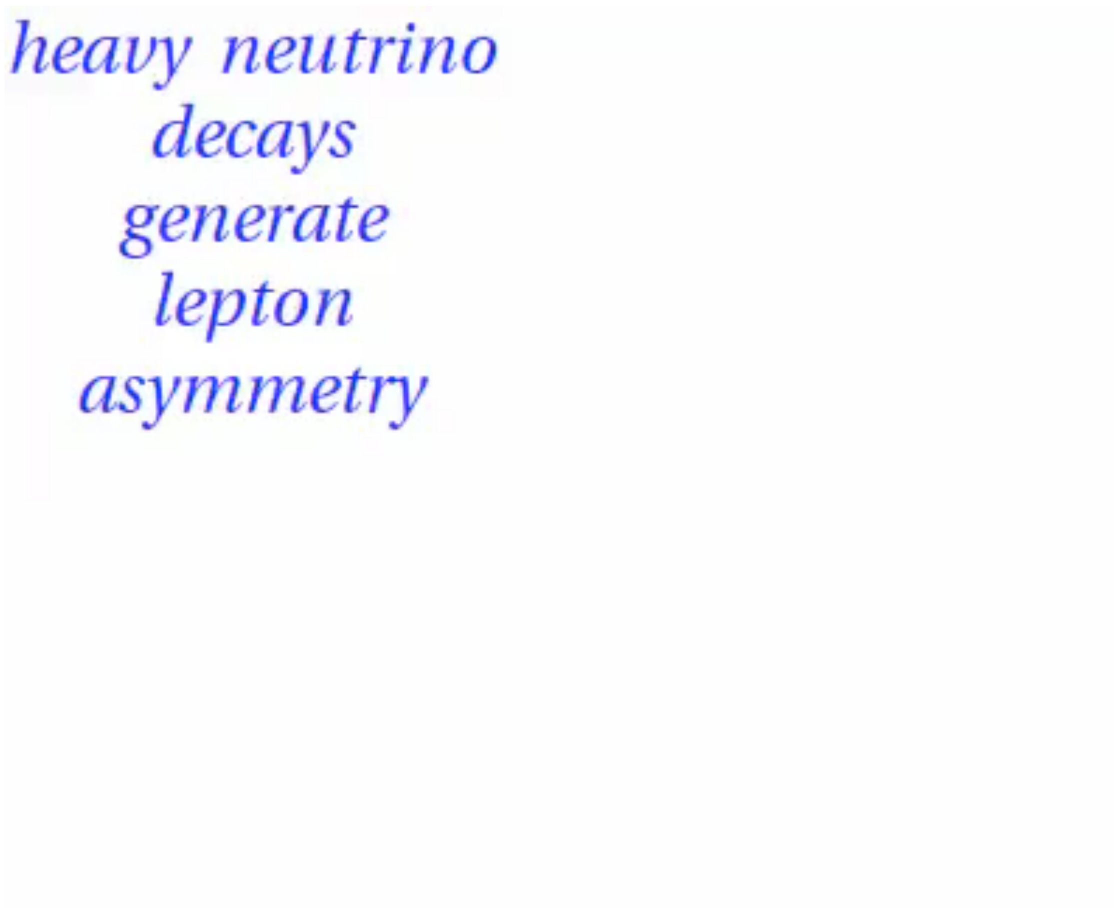
Buchmuller, Plumacher, 1998; Buchmuller, Di Bari, Plumacher, 2004

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

(k: inverse decay ΔL=1, scattering processes ΔL=1, 2)

Primordial ΔL from Heavy Neutrino Decay

[Animation Credit: Michael Ratz]

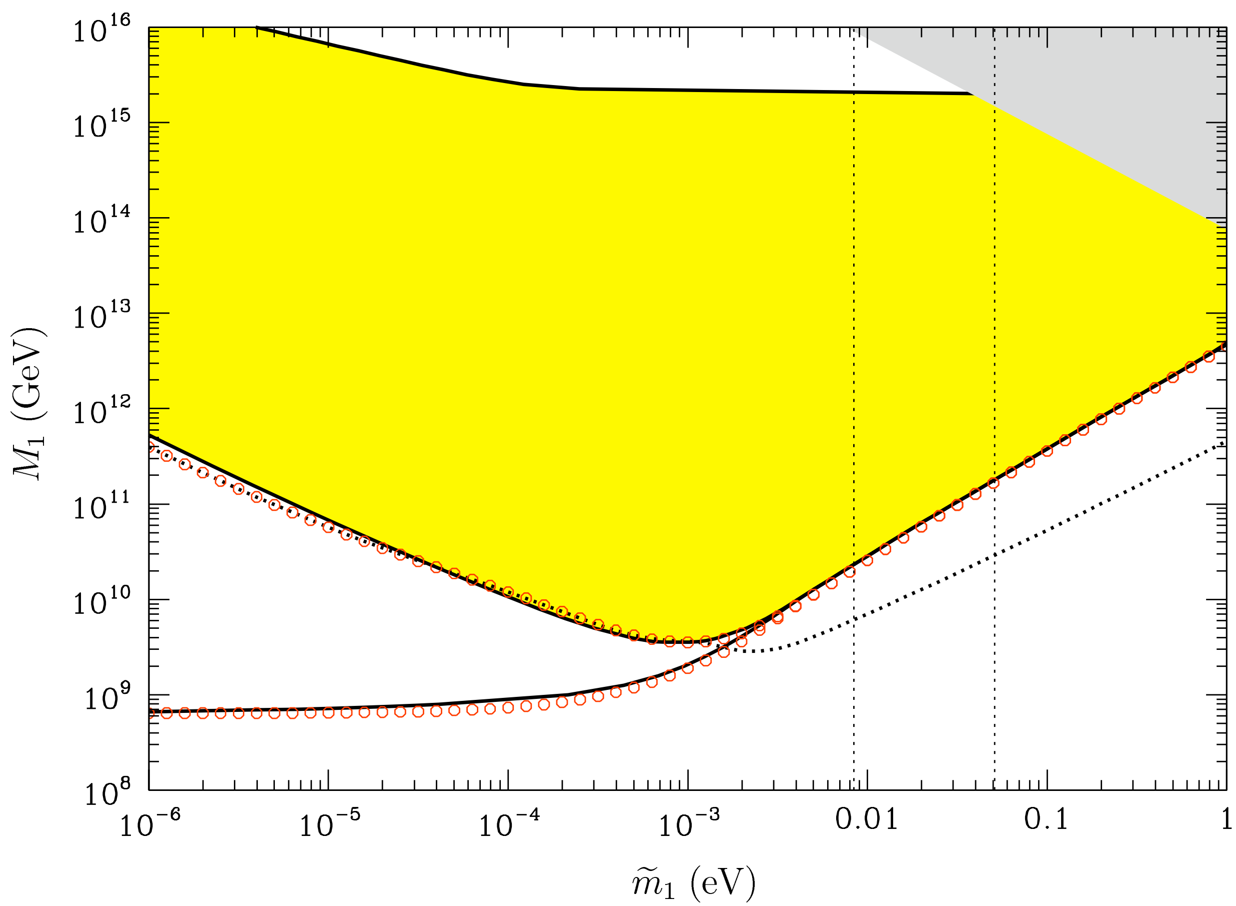


Sphaleron Converting ΔL → ΔB

[Animation Credit: Michael Ratz]

Bound on Light Neutrino Mass

- sufficient leptogenesis requires $M_1 \geq 2 \times 10^9$ GeV
- bound on light neutrino mass



Buchmuller, Di Bari, Plumacher, 2005

Gravitino Problem

- Thermally produced RH neutrino N:
  - high reheating temperature needed:

$$\Rightarrow \quad T_{RH} > M_R > 2 \times 10^9 \text{ GeV}$$

- over-production of light state: gravitinos

- For gravitinos LSP:
  - DM constraint from WMAP
  - stringent bound on gluino mass for any given gravitino mass & T_{RH}

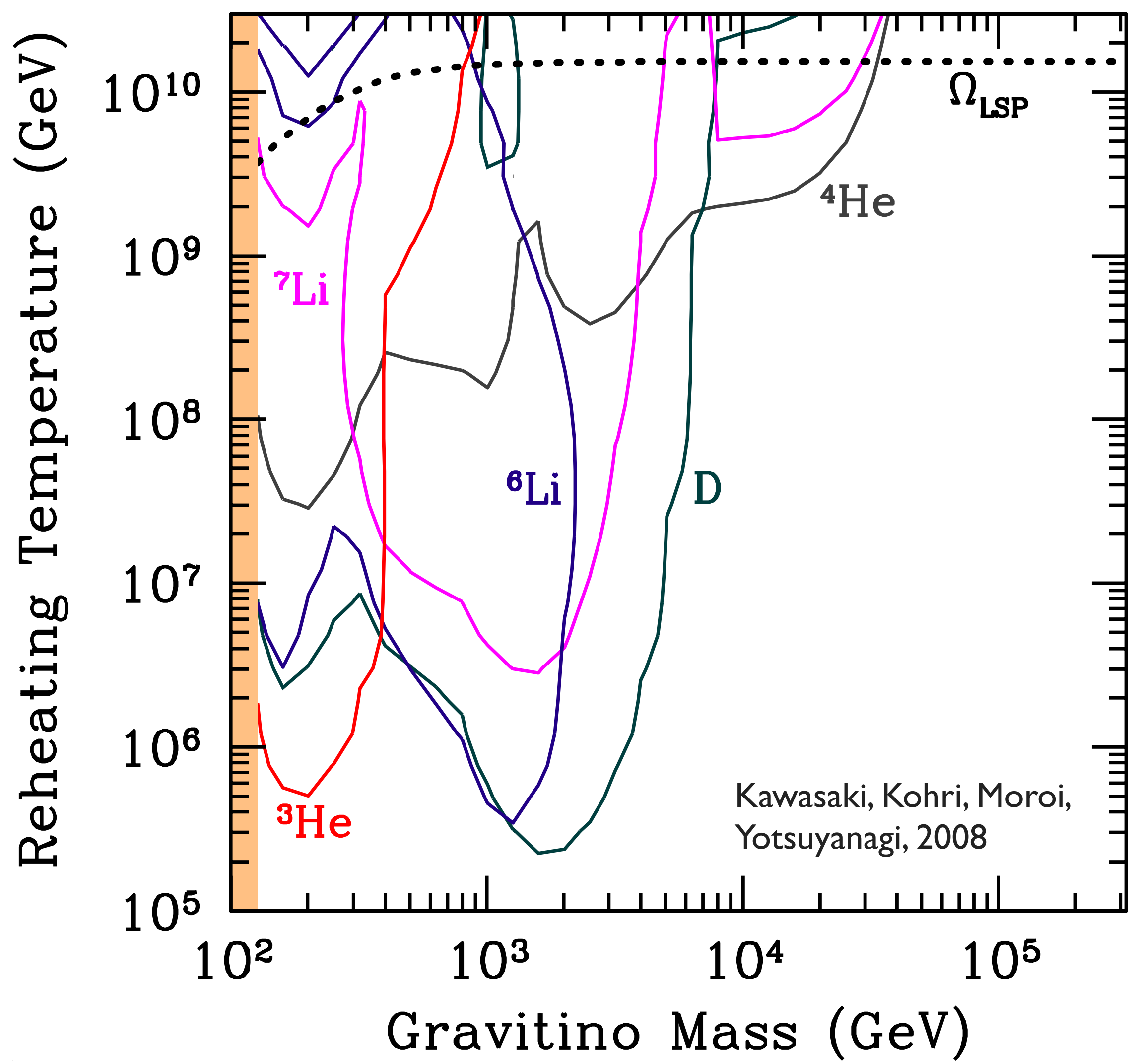
- For unstable gravitinos:
  - long life time
  - decay during and after BBN ⇒ affect abundance of light elements

Gravitino Problem

For light gravitino mass,

BBN constraints

⇒ $T_{RH} < 10^{(5\text{-}6)}$ GeV



Gravitino Problem

For light gravitino mass,

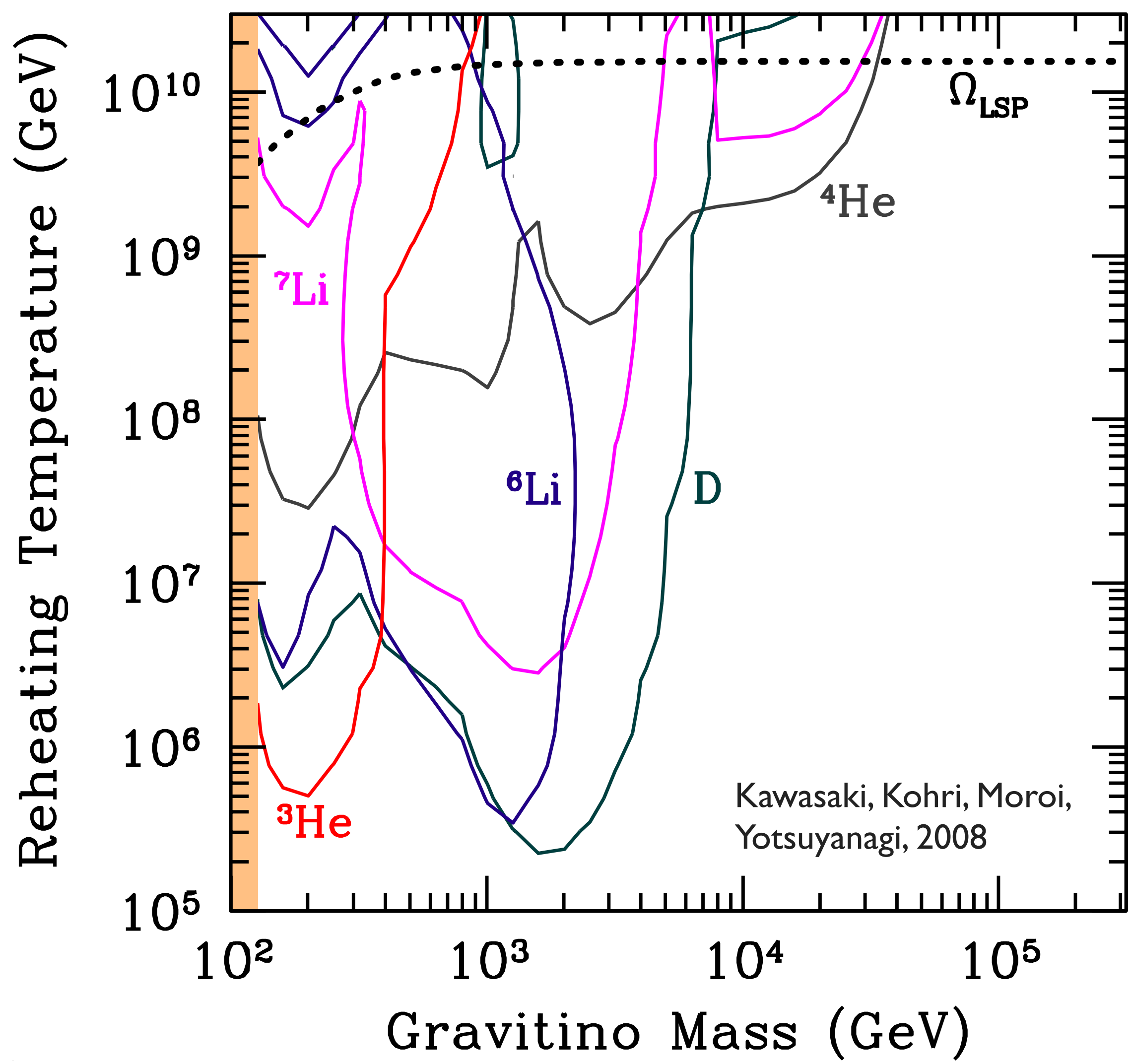
BBN constraints

$\Rightarrow T_{RH} < 10^{(5\text{-}6)}$ GeV

tension!

Sufficient leptogenesis

$\Rightarrow T_{RH} > M_R > 2 \times 10^9$ GeV

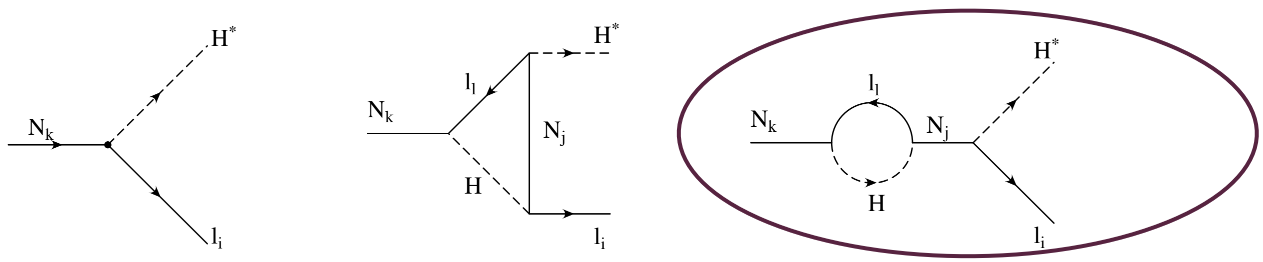


Alternatives: “Non-standard” Scenarios

- Possible ways to avoid the tension:
  - resonant enhancement in self-energy diagram ⇒ lowering M_R, thus T_{RH}

    ➔ resonant leptogenesis (near degenerate RH neutrinos) Pilaftsis, 1997

    Recall: in standard leptogenesis:



self-energy diagram dominate for near degenerate RH neutrino masses, $M_{1,2}$

enhanced O(1) asymmetry possible if

$$M_1 - M_2 \sim \frac{1}{2}\Gamma_{N_{1,2}} \quad , \quad \text{assuming} \quad \frac{Im(h_\nu h_\nu^\dagger)_{12}^2}{(h_\nu h_\nu^\dagger)_{11}(h_\nu h_\nu^\dagger)_{22}} \sim 1$$

leptogenesis possible even for low $M_{1,2}$

Pilaftsis, Underwood, 2003

Alternatives: "Non-standard" Scenarios

- Possible ways to avoid the tension:
  - relaxing relations between lepton number asymmetry and RH nu mass
    ➔ soft leptogenesis (SUSY CP phases) Boubekeur, 2002; Grossman, Kashti, Nir, Roulet, 2003; D'Ambrosio, Giudice, Raidal, 2003;

    CP asymmetry in decay → standard leptogenesis
    CP asymmetry in mixing → soft leptogenesis

    soft SUSY breaking ⇒ mismatch between mass eigenstates and CP eigenstates of heavy sneutrinos ⇒ asymmetry

    $$\epsilon = \left(\frac{4\Gamma_1 B}{\Gamma_1^2 + 4B^2} \right) \frac{\mathrm{Im}(A)}{M_1} \delta_{B-F}$$

    A, B: SUSY CP-violating phases
    lose connection to neutrino oscillation

  - relaxing relation between T_{RH} and RH neutrino mass
    ➔ non-thermal leptogenesis (non-thermal production of RH neutrinos)

    Inflaton decay: $\Phi \longrightarrow N_1 + N_1$ $m_\Phi > 2M_1$ Fuji, Hamaguchi, Yanagida, 2002

Dirac Leptogenesis

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

- 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 > Tew
- If L stored in RH fermions can survive below EW phase transition, net lepton number can be generated even with L=0 initially

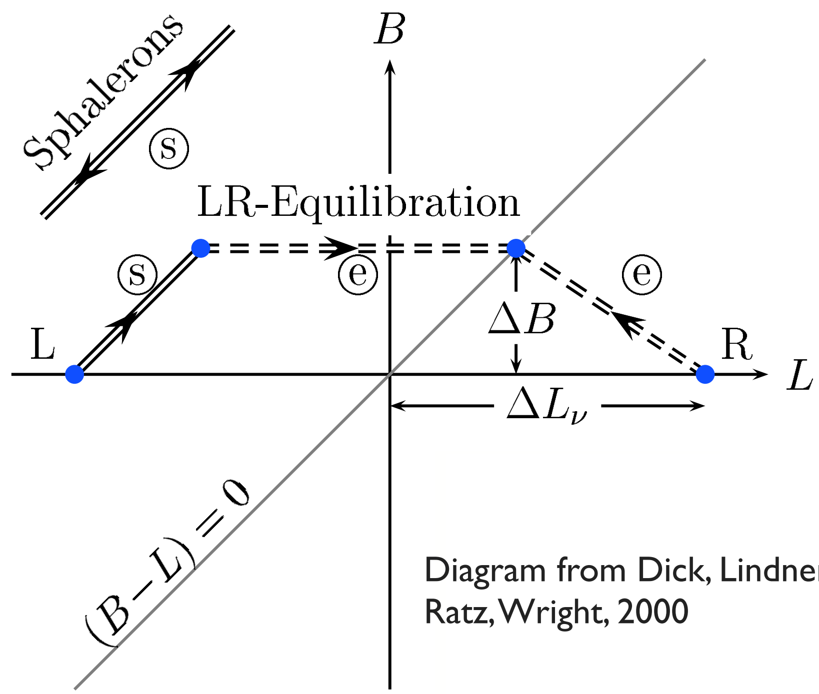
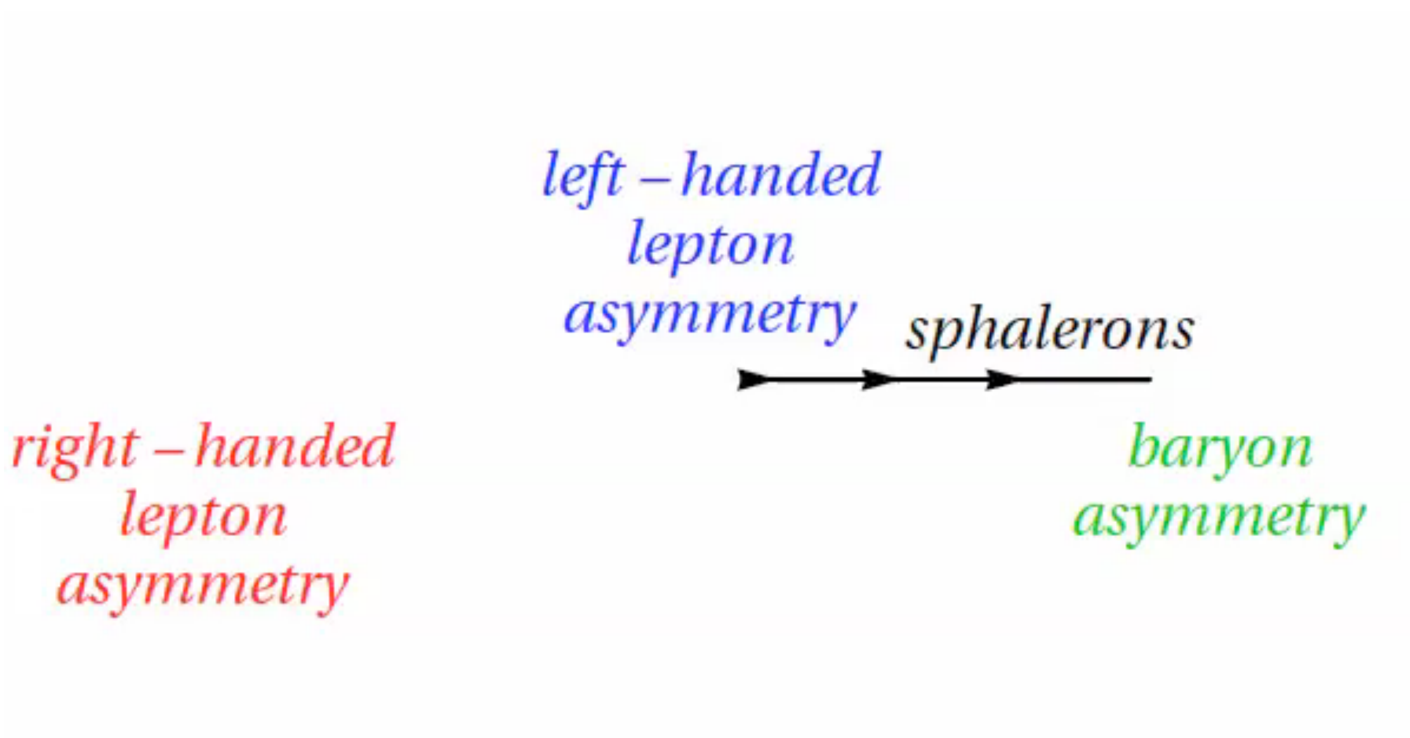


Diagram from Dick, Lindner, Ratz, Wright, 2000

Dirac Leptogenesis

[Animation Credit: Michael Ratz]

Dirac Leptogenesis



[Animation Credit: Michael Ratz]

Dirac Leptogenesis

- for neutrinos: LH equilibration can occur 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, to appear
    - 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

Testing Leptogenesis?

- Sakharov Conditions:
  - out-of-equilibrium
    - ➡ expanding Universe
    - ➡ smallness of neutrino masses
      - → Leptogenesis with Majorana neutrino: heavy field decay
      - → Dirac Leptogenesis: late equilibration temperature
  - 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
  - CP violation
    - ➡ Long baseline neutrino oscillation experiments

Connection to Low Energy Observables

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

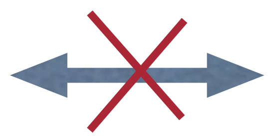
  6 mixing angles + 6 physical phases

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

  3 mixing angles + 3 physical phases

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

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



leptogenesis ≠ 0

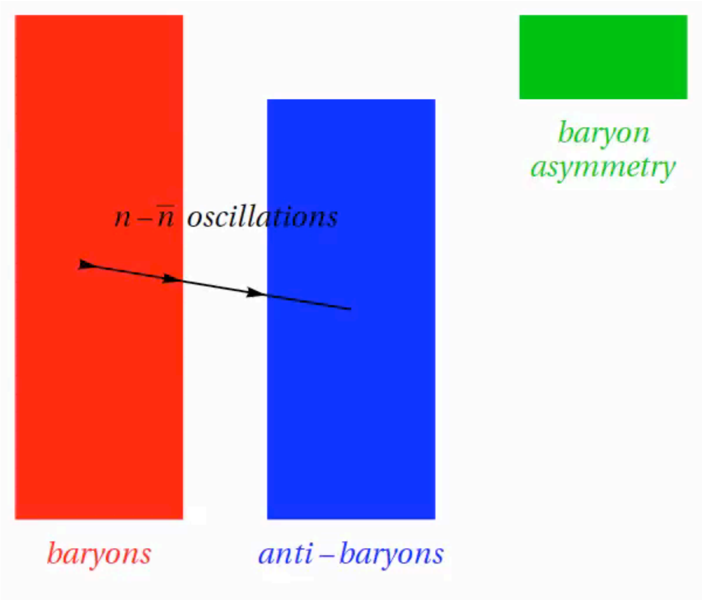
- No model independent connection
- Statement is weakened when the so-called flavor effects are taken into account (relevant if leptogenesis at $T < 10^{12}$ GeV)
- BUT, in certain models, connection can be established even without the flavor

Connection in Specific Models

- models for neutrino masses:
  - additional symmetries
  - reduce the number of parameters ⇒ connection can be established
- rank-2 mass matrix (may be realized by symmetry)
  - models with 2 RH neutrinos (2 x 3 seesaw) Kuchimanchi & Mohapatra, 2002
  - sign of baryon asymmetry ↔ sign of CPV in ν oscillation Frampton, Glashow, Yanagida, 2002
- all CP come from a single source
  - models with spontaneous CP violation:
    - minimal LR model: only 1 physical leptonic CP phase M.-.C.C, Mahanthappa, 2005
    - SM + vectorial quarks + singlet scalar Branco, Parada, Rebelo, 2003
    - SCPV in SO(10): $<126>_{B-L}$ complex Achiman, 2004, 2008
  - SUSY SU(5) x T′ Model: M.-.C.C, Mahanthappa, 2009
    - group theoretical origin of CP violation ⇒ only low energy lepton phases ≠ 0

Neutron-Antineutron Oscillation

- Neutrino Experiments → “archeological” evidence for leptogenesis
- 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 $10^{(5\text{-}6)}$ GeV
  - erasure of matter-antimatter generated at high scale, e.g. standard leptogenesis
- Low scale leptogenesis scenarios preferred:
  - Dirac Leptogenesis
  - Resonance Leptogenesis
  - .....



[Animation Credit: Michael Ratz]

Conclusions

- origin of matter: one of the great mysteries in particle physics and cosmology
- leptogenesis: an appealing baryogenesis mechanism connected to neutrino physics
- various leptogenesis mechanisms:
  - standard leptogenesis: gravitino problem, incompatible with SUSY
  - resonance leptogenesis
  - Dirac leptogenesis

- While there is no model-independent way to test leptogenesis, searches at neutrino experiments (leptonic CPV, neutrino-less double beta decay) can provide supports for/distinguish among the mechanisms
- neutron-antineutron oscillation: complementarity test
  - if observed $\Rightarrow$ low scale leptogenesis scenarios preferred