Leptogenesis

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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

- neutrino masses open up a new possibility

Fukugita, Yanagida, 1986

  - new CP phases in lepton sector

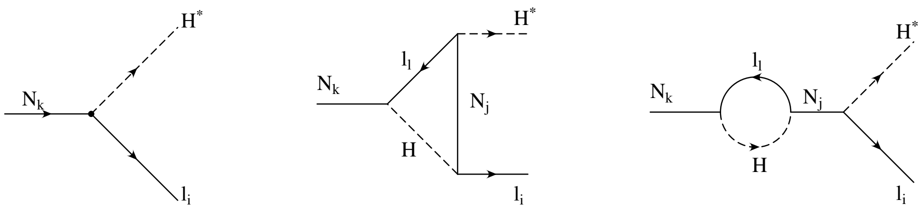
Leptogenesis

- Predictions closely tied to properties of neutrinos

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)

Bound on Light Neutrino Mass

- sufficient leptogenesis requires

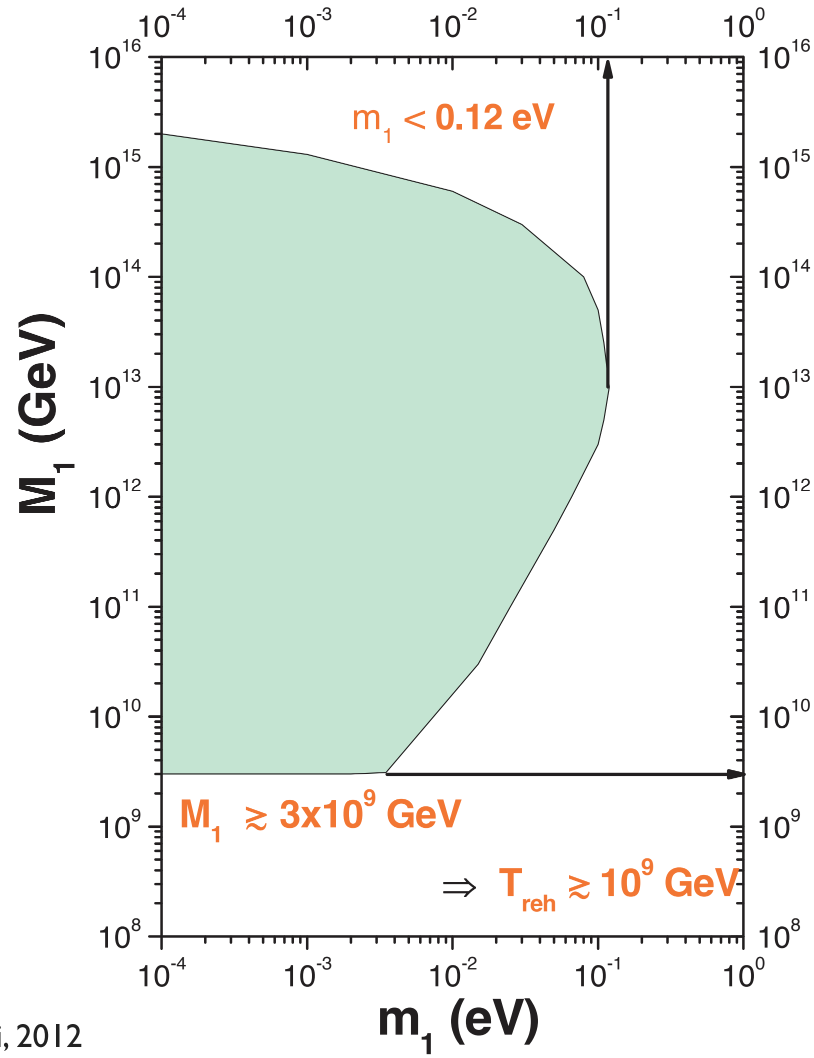
  $M_1 \gtrsim 3\text{x}10^9$ GeV

- upper bound on light neutrino mass

  $m_1 < 0.12$ eV

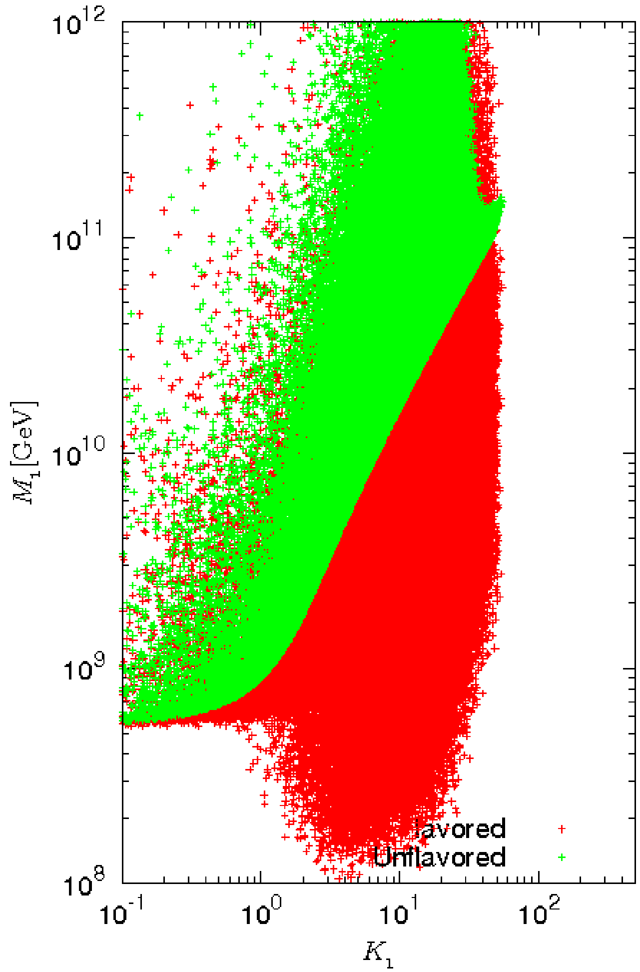
  - incompatible with quasi-degenerate spectrum

- constraints slightly alleviated with flavored case



P. Di Bari, 2012

Bound on Light Neutrino Mass



P. Di Bari, 2012

Gravitino Problem

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

$$\Rightarrow \quad T_{RH} > M_R > O(10^9)\text{GeV}$$

- 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}

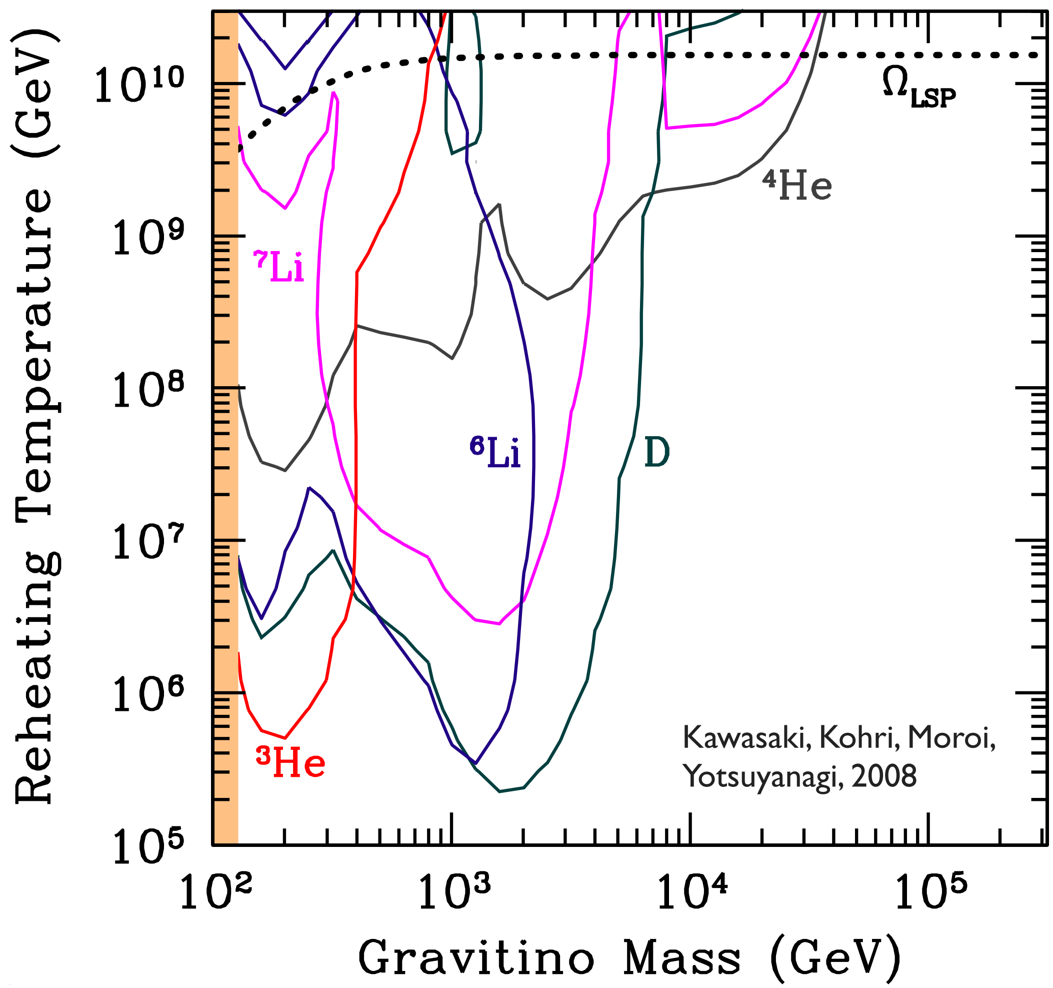
- For unstable gravitinos:
  - long life time
  - decay during and after BBN ⇒ affect abundance of light elements

Gravitino Problem

For light gravitino mass,

BBN constraints

⇒ $T_{RH} < 10^{(5\text{-}6)}$ GeV



Gravitino Problem

For light gravitino mass,

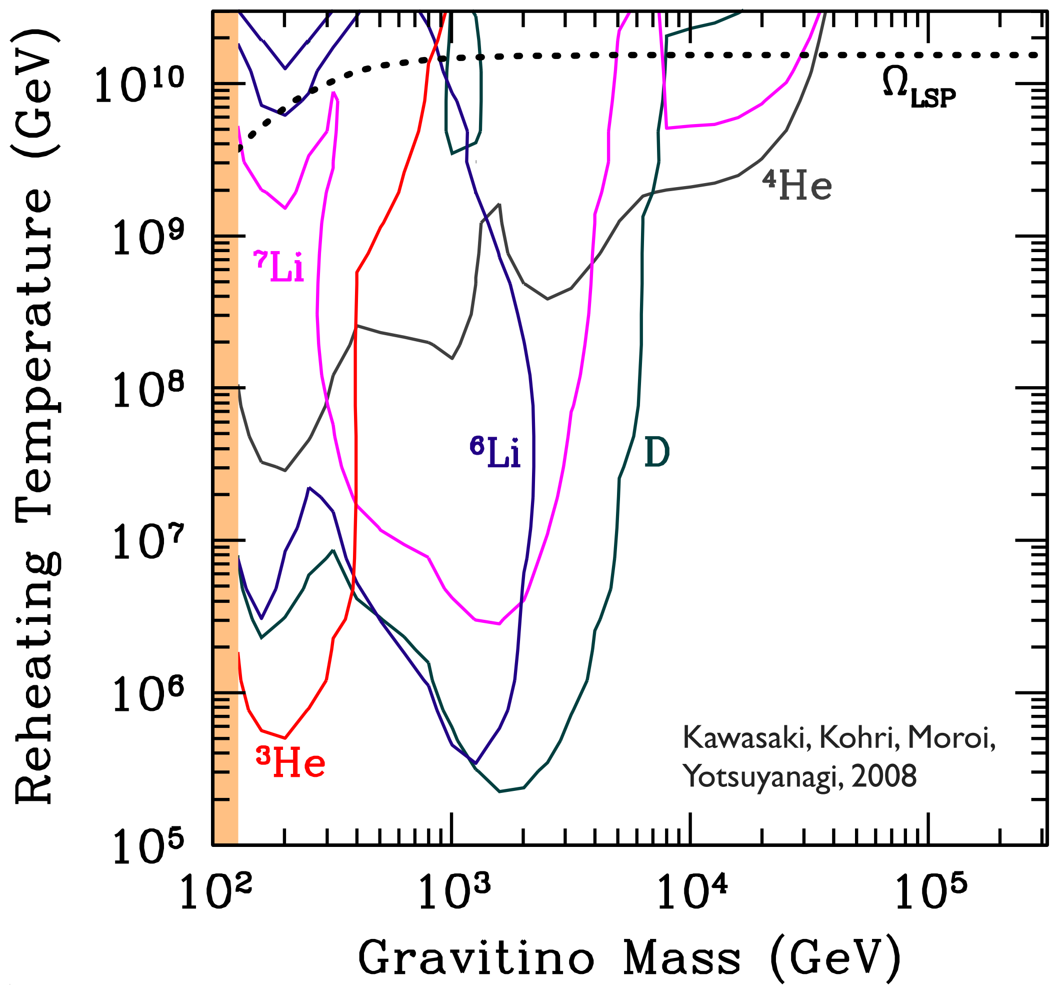
BBN constraints

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

tension!
(if SUSY)

Sufficient leptogenesis $\Rightarrow$

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

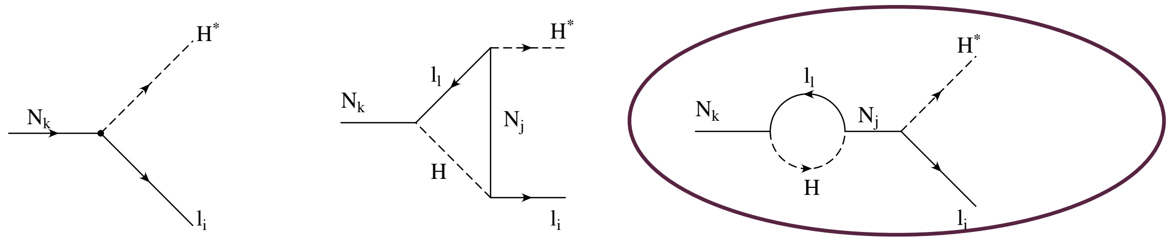


Alternatives: "Non-standard" Scenarios

- 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

  - possible collider test

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

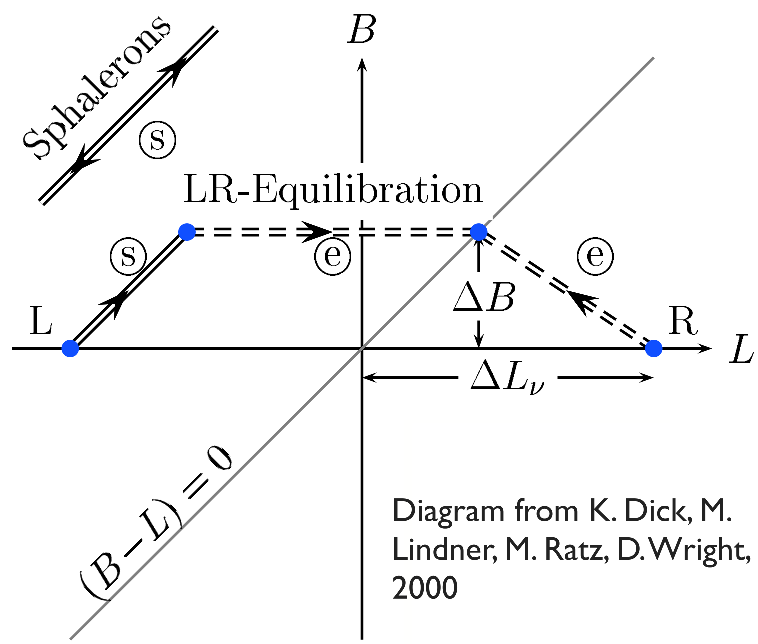


Diagram from K. Dick, M. Lindner, M. Ratz, D. Wright, 2000

late time LR equilibration of neutrinos making Dirac leptogenesis possible

Dirac Leptogenesis

- for neutrinos: LH equilibration can occur at late time ($T_{eq} \ll T_{EW}$) because of their much suppressed masses ($m_D < 10\ \mathrm{keV}$)
- 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

Testing Leptogenesis?

- Sakharov Conditions:
  - out-of-equilibrium
    - ➡ expanding Universe
    - ➡ smallness of neutrino masses

Leptogenesis with Majorana neutrino: out-of-equilibrium 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)

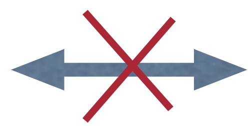
  6 mixing angles + 6 physical phases

- 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 effects

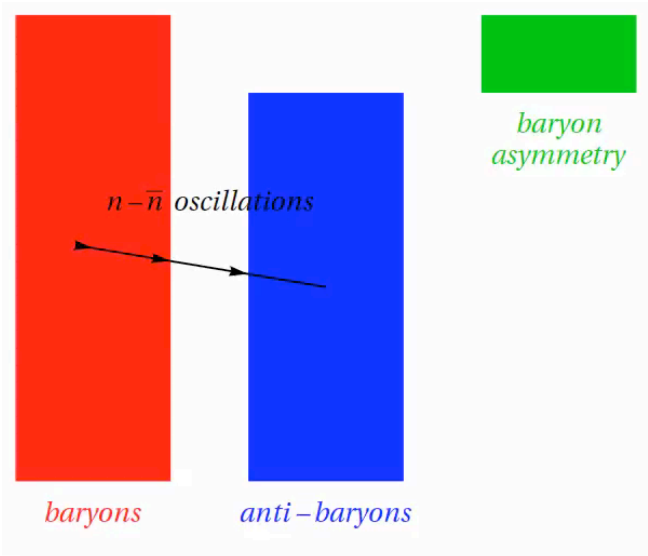
Connection in Specific Models

- 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:
    - SM + vectorial quarks + singlet scalar Branco, Parada, Rebelo, 2003
    - minimal LR model: only 1 physical leptonic CP phase M.-.C.C, Mahanthappa, 2005
    - SCPV in SO(10): $\langle 126 \rangle_{B-L}$ 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

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 $10^{(5\text{-}6)}$ GeV
  - erasure of matter-antimatter generated at high scale, e.g. standard leptogenesis

Babu, Mohapatra, 2012



[Animation Credit: Michael Ratz]

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

Quantum Boltzmann Equations

- Classical vs Quantum Boltzmann equations:
  - collision terms: involving quantum interference
  - time evolution: require full quantum mechanical treatment
  - Classical Boltzmann equations not sufficient

Buchmuller, Fredenhagen, 2000;
Simone, Riotto 2007;
Lindner, Muller 2007

- Classical Boltzmann equations:
  - scattering independent from previous ones
- Quantum Boltzmann equations:
  - Closed-Time-Path (CTP) formulation for non-equilibrium QFT
  - involve time integration for scattering terms
  - "memory effects": time-dependent CP asymmetry

Schwinger, 1961; Mahanthappa, 1962;
Bakshi, Mahanthappa, 1963;
Keldysh, 1965

Quantum Boltzmann Equations

- time scale of Kernel << relaxation time scale ~ $(\Gamma_{N1})^{-1}$
  - Classical Boltzmann equations ≈ Quantum Boltzmass equations

- In resonance leptogenesis: $\Delta M = (M_2 - M_1) \sim \Gamma_{N2}$
  - Kernel time scale ~ $(\Delta M)^{-1} > (\Gamma_{N1})^{-1}$ possible
  - Quantum Boltzmann equations important!!

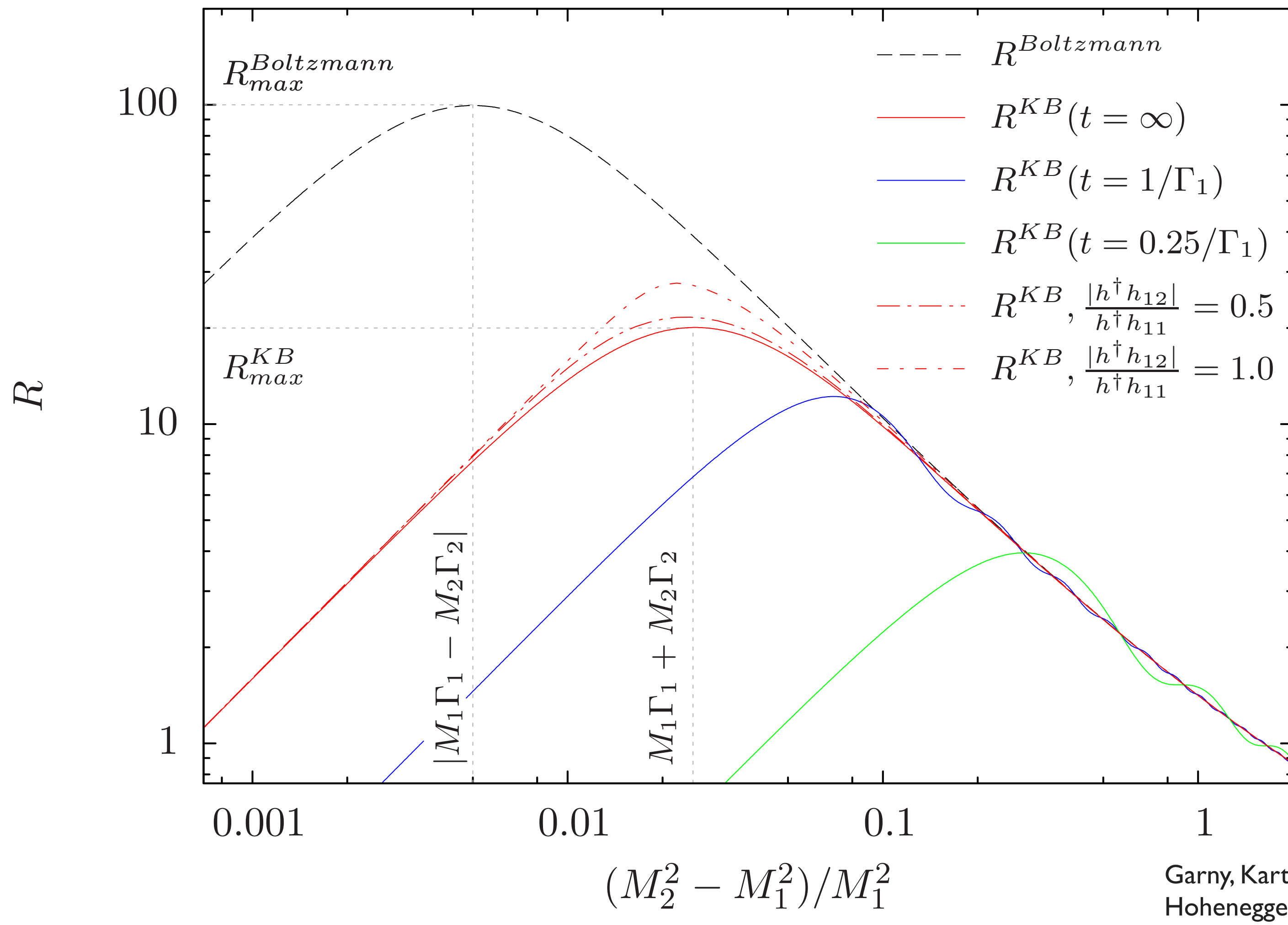
$$R_{max}^{Boltzmann} = \frac{M_1 M_2}{2|M_1\Gamma_1 - M_2\Gamma_2|}$$

Garny, Kartavtsev, Hohenegger, 2011

$$R_{max}^{KB} = \frac{M_1 M_2}{2(M_1\Gamma_1 + M_2\Gamma_2)}$$

resonance behavior confirmed by full quantum treatment; though amplitude reduced

Quantum Boltzmann Equations



Garny, Kartavtsev, Hohenegger, 2011

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, incompatible 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)
  - Neutrino-less double beta decay (Majorana vs Dirac leptogenesis)
- model-dependently: connections to CPV in other sectors possible
  - searches at neutrino experiments (leptonic CPV, mixing parameters)
  - complementarity test from other B or L violating processes
    - e.g. N-Nbar oscillation ⇒ constraint scale of leptogenesis

- Toward Theory of Leptogenesis: Quantum Boltzmann equation (non-equilibrium QFT)