Neutrinos and the Origin of Matter

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Outline

- Introduction: two problems
- One solution: Leptogenesis (in type I seesaw)
- Constraints on neutrino parameters
- Challenges and opportunities
- Conclusions

Introduction

The universe as a baby:

Hot and dense plasma of elementary particles

Described by combination of general relativity, particle physics and thermodynamics.

$\rightarrow$ complementary to earth-based experiments.

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Carl von Clausewitz:

Cosmology is the continuation of particle physics by other means

Introduction

Problem #1: The universe is made of matter.

Baryon asymmetry (from nucleosynthesis and CMB):

$$\eta_B \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 6 \times 10^{-10}$$

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Possible explanations:

- **Symmetric cosmology:**
  nucleons and anti-nucleons annihilate until $T \sim 20\,\mathrm{MeV} \Rightarrow$
  residual nucleon to photon ratio $\sim 10^{-18}$
- η_B **as initial condition:** not compatible with inflation
- **Matter and antimatter got separated:** at $T \sim 20\,\mathrm{MeV}$
  causally connected region contained $\sim 10^{-5} M_\odot$

Introduction

Problem #1: The universe is made of matter.

Baryon asymmetry (from nucleosynthesis and CMB):

$$\eta_B \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 6 \times 10^{-10}$$

must have been generated during evolution of universe!

Necessary ingredients (Sakharov, 1967)

- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium

Sakharov's third condition

System in thermal equilibrium described by density operator

$$\rho = \mathrm{e}^{-H/T}, \qquad \text{where } H: \text{ Hamiltonian}$$

time evolution of baryon number B:

$$\begin{aligned} B(t) &= \mathrm{e}^{iHt} B(0) \, \mathrm{e}^{-iHt} \\ \Rightarrow \langle B(t) \rangle_T &= \mathrm{Tr}\left(\mathrm{e}^{-H/T} \, \mathrm{e}^{iHt} B(0) \, \mathrm{e}^{-iHt} \right) \\ &= \mathrm{Tr}\left(\mathrm{e}^{-iHt} \, \mathrm{e}^{-H/T} \, \mathrm{e}^{iHt} B(0) \right) \\ &= \langle B(0) \rangle_T \end{aligned}$$

Baryon number is constant in thermal equilibrium

Sakharov's third condition

Baryon number B is odd under C, even under P and T
$\Rightarrow B$ is odd under $CPT \equiv \theta$

Thermal average of baryon number:

$$\begin{aligned}
\langle B \rangle_T &= \mathrm{Tr}\left(\mathrm{e}^{-H/T} B\right) \\
&= \mathrm{Tr}\left(\theta^{-1} \theta\, \mathrm{e}^{-H/T} B\right) \\
&= \mathrm{Tr}\left(\mathrm{e}^{-H/T} \theta B \theta^{-1}\right) \\
&= -\langle B \rangle_T
\end{aligned}$$

No baryon asymmetry can be generated in thermal equilibrium!

Neutrino masses

- direct mass searches: $m_\nu \lesssim 2\,\text{eV}$
- Neutrino flavour oscillations:

  atmospheric ν oscillations: $\Rightarrow m_{\nu_i} \gtrsim 0.05\,\text{eV}$

  solar ν oscillations: $\Rightarrow m_{\nu_j} \gtrsim 0.008\,\text{eV}$

Problem #2:

ν masses are $\neq 0$ but orders of magnitude smaller than any other known masses

Both problems, BAU and ν masses, cannot be solved in the SM $\Rightarrow$ need extended model

Standard Model:

- left- and right-handed quarks and charged leptons
- neutrinos only left-handed. Why?

Introduce right-handed neutrinos N

First prediction: neutrino masses (type I seesaw)

Seesaw

$$m_\nu \sim \frac{v^2}{M}$$

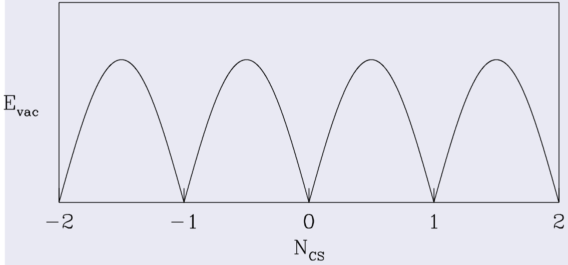
$v \sim 100\,\mathrm{GeV}$: SM mass scale; M: mass of N.
Observed light neutrino masses yield clues on M

$$m_\nu \gtrsim 0.05\,\mathrm{eV} \quad \Rightarrow \quad M \lesssim 10^{14}\,\mathrm{GeV}$$

Second prediction: lepton number L is violated
Why do we care?

Baryon and lepton number violation

Vacuum structure of non-Abelian gauge theories:



Topological charge:

('t Hooft '76)

$$\Delta B = \Delta L = n_f \Delta N_{CS}$$

Transition rate:

$$T = 0: \qquad \mathrm{e}^{-4\pi/\alpha_w} \sim 10^{-170}$$

$$T > 0: \qquad \mathrm{e}^{-E_{sph}/T} \quad \text{with} \quad E_{sph} \sim \frac{8\pi v(T)}{g}$$

$$T > T_{ew}: \qquad \alpha_w^5 T^4$$

(Bödeker '98)

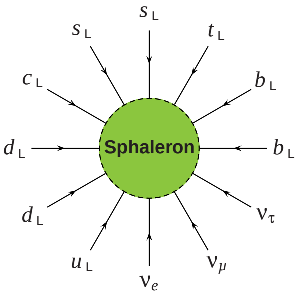
SM: $B+L$ is violated by instantons

(Klinkhammer & Manton ’84; Kuzmin et al. ’85)

Sphalerons are in thermal equilibrium above electroweak ‘phase transition’:

$$T_{ew} \sim 100\ \mathrm{GeV} \lesssim T \lesssim 10^{12}\,\mathrm{GeV}$$

$B+L$ violated, $B-L$ conserved.



B and L are not independent at $T \gtrsim 100\,\mathrm{GeV}$

$$\eta_B = c\,\eta_{B-L} = \frac{c}{c-1}\,\eta_L\,, \qquad \text{with} \qquad c \sim \frac{1}{3}$$

L violating processes can generate η_B!

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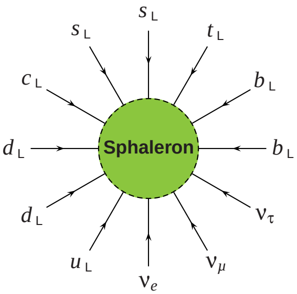

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Leptogenesis

A free lunch: Leptogenesis in type I seesaw

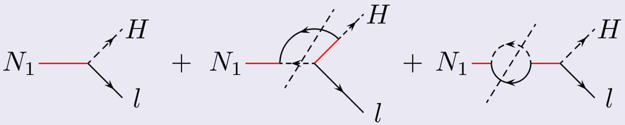
Right-handed neutrinos can also give rise to η_B (Fukugita and Yanagida '86)
Yukawa couplings:

$$\mathscr{L}_Y \simeq \overline{N}\,\lambda_\nu\, l H - \overline{N} M N$$

- Ns are unstable, decay to lepton-Higgs pairs:

$$\Gamma_D \propto \widetilde{m}_1 = \frac{v^2}{M_1}(\lambda_\nu^\dagger \lambda_\nu)_{11}$$

- N interactions violate $L \to L \neq 0$, partially converted to $B \neq 0$ by sphalerons
- λ_ν complex $\Rightarrow$ CP violation ε_i



Out-of-equilibrium condition:

The N_1 are not in thermal equilibrium if N decay width Γ_D smaller than expansion rate H:

$$\Gamma_D < H(T)$$

$\Rightarrow$ upper bound on effective light neutrino mass:

$$\widetilde{m}_1 \lesssim 10^{-3}\,\mathrm{eV} \quad \text{with} \quad \widetilde{m}_1 = \frac{v^2}{M_1}(\lambda_\nu^\dagger \lambda_\nu)_{11}$$

Scale of light neutrino masses

$\sqrt{\Delta m^2_{\mathrm{sol}}} \simeq 8 \times 10^{-3}\,\mathrm{eV}$ and $\sqrt{\Delta m^2_{\mathrm{atm}}} \simeq 5 \times 10^{-2}\,\mathrm{eV}$

since $m_{\nu_1} \leq \widetilde{m}_1 \rightsquigarrow$ deviations from thermal equilibrium small (?)

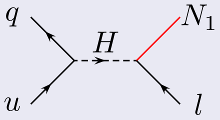
Challenge #1: How do the N get produced?

(Luty ’92; M.P. ’96; Pilaftsis and Underwood ’03)

N scattering processes are important

all production processes $\propto \widetilde{m}_1$

need large $\widetilde{m}_1$ for efficient production



Challenge #2: L violating scatterings can destroy η_B

(Fukugita & Yanagida ’90; Buchmüller, Di Bari & M.P. ’02; Giudice et al. ’03)

Two contributions to reaction rate:

- resonant contribution from N_1: $\propto \widetilde{m}_1$
- remainder: $\propto M_1 \overline{m}^2$, $\overline{m}^2 = \sum m_{\nu_i}^2$

need small $\widetilde{m}_1$ and $M_1 \overline{m}^2$ to avoid washout

Two conflicting requirements

$\longrightarrow$ network of Boltzmann equations

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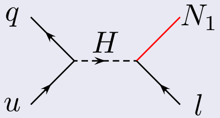

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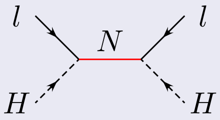

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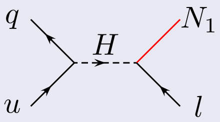

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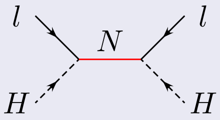

Two conflicting requirements

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Quantitative analysis via Boltzmann equations

competition between production and washout:

$$\frac{dN_{N_1}}{dz} = -(D+S)\,(N_{N_1} - N_{N_1}^{\mathrm{eq}})$$

$$\frac{dN_{B-L}}{dz} = -\varepsilon_1\, D\,(N_{N_1} - N_{N_1}^{\mathrm{eq}}) - W\, N_{B-L}$$

$z = M_1/T \quad \propto \sqrt{t}$

N_i : number densities in comoving volume

D : decays

S : $\Delta L = 1$ scatterings

W : washout due to L violating scatterings

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produced baryon asymmetry:

$$\eta_B \simeq 10^{-2}\,\varepsilon_1\,\kappa(\widetilde{m}_1, M_1\overline{m}^2)$$

need to know:

- CP asymmetry ε_1 (from neutrino mass model)
- efficiency factor κ parametrizes N interactions (from integration of Boltzmann eqs.)

(Barbieri et al. '00; Buchmüller, Di Bari & M.P. '02)

Baryon asymmetry determined by four parameters

1. CP asymmetry ε_1
2. mass of decaying neutrino M_1
3. effective light neutrino mass (coupling strength of N_1)

$$\widetilde{m}_1 = \frac{v^2}{M_1}\left(\lambda_\nu^\dagger \lambda_\nu\right)_{11}$$

4. light neutrino masses

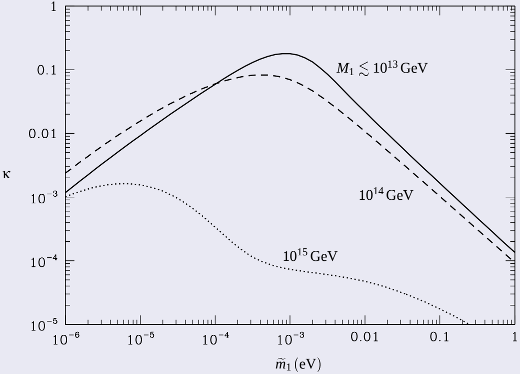
$$\overline{m} = \sqrt{m_{\nu_1}^2 + m_{\nu_2}^2 + m_{\nu_3}^2}$$

since

$$\Gamma_{\Delta L=2} \propto M_1 \overline{m}^2$$

Efficiency factor κ as function of $\widetilde{m}_1$

(M.P. '96; Buchmüller, Di Bari & M.P. '02)



hierarchical light νs:
$\overline{m} = 0.05\,\mathrm{eV}$

maximal efficiency:

$\kappa^{\max} \simeq 0.18$

for $\widetilde{m}_1 \simeq 10^{-3}\,\mathrm{eV}$
and $M_1 \lesssim 10^{13}\,\mathrm{GeV}$

$\longrightarrow$ N interactions reduce efficiency:

- for $\widetilde{m}_1 \ll 10^{-3}\,\mathrm{eV}$: N production inefficient
- for $\widetilde{m}_1 \gg 10^{-3}\,\mathrm{eV}$: washout too strong
- for $M_1 \gtrsim 10^{13}\,\mathrm{GeV}$: $\Gamma_{\Delta L=2} \propto M_1 \overline{m}^2$ becomes important

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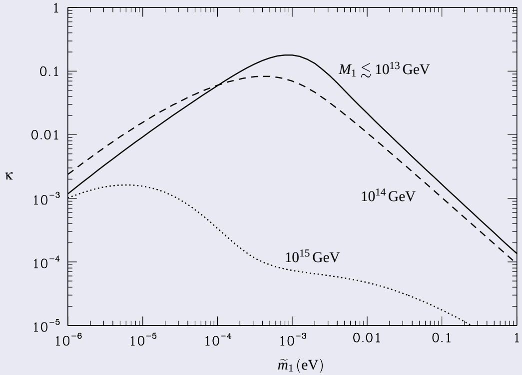

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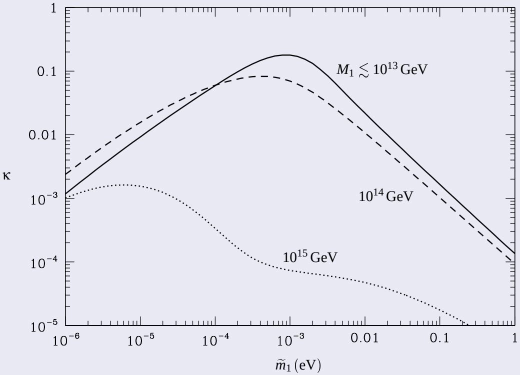

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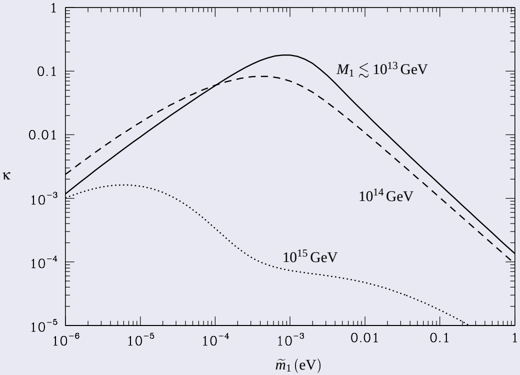

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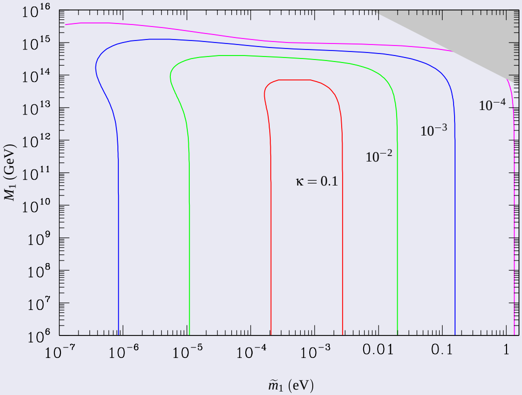
lines of constant κ in $(\widetilde{m}_1, M_1)$ plane



hierarchical light ν's:
$\overline{m} = 0.05\,\mathrm{eV}$

maximal efficiency in the mass range

$$10^{-4}\,\mathrm{eV} \lesssim \widetilde{m}_1 \lesssim 10^{-2}\,\mathrm{eV}$$

$$M_1 \lesssim 10^{13}\,\mathrm{GeV}$$

Baryon asymmetry determined by four parameters

1. *CP* asymmetry ε_1
2. mass of decaying neutrino M_1
3. effective light neutrino mass $\widetilde{m}_1$ ($\propto$ decay width of N_1)
4. light neutrino masses $\overline{m} = \sqrt{m_{\nu_1}^2 + m_{\nu_2}^2 + m_{\nu_3}^2}$

Final baryon asymmetry

$$\eta_B \simeq 10^{-2}\, \varepsilon_1\, \kappa(\widetilde{m}_1, M_1 \overline{m}^2)$$

need to know:

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CP asymmetry

$$\varepsilon_1 = \frac{\Gamma(N \to l) - \Gamma(N \to \bar{l})}{\Gamma(N \to l) + \Gamma(N \to \bar{l})}$$

for $M_{2,3} \gg M_1$: upper bound on ε_1 in terms of light ν masses:

(Davidson & Ibarra ’02; Buchmüller, Di Bari & M.P. ’03; Hambye et al. ’03)

$$\varepsilon_1^{\max} = \frac{3}{16\pi} \frac{M_1 m_{\nu_3}}{v^2} f\left(m_{\nu_i}, \widetilde{m}_1\right)$$

two limiting cases:

- hierarchical light νs: $m_{\nu_1} \to 0 \quad \Rightarrow \quad \varepsilon_1^{\max} = \frac{3}{16\pi} \frac{M_1 m_{\nu_3}}{v^2}$
- degenerate light νs: $m_{\nu_3} = m_{\nu_1} \quad \Rightarrow \quad \varepsilon_1^{\max} = 0$

$\to$ *CP* asymm. suppressed if light ν spectrum quasi-degenerate

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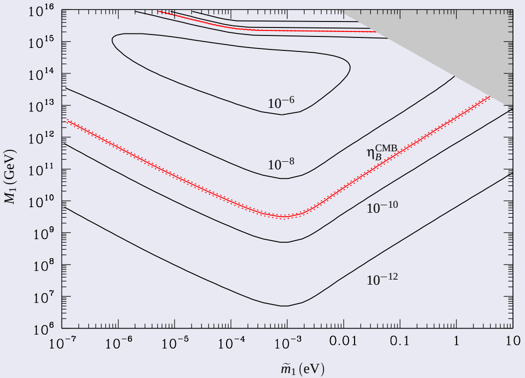
Maximal baryon asymmetry

$$\eta_B^{\max} = 10^{-2}\, \varepsilon_1^{\max}\, \kappa(\widetilde{m}_1, M_1 \overline{m}^2)$$

hierarchical light νs: $\overline{m} = 0.05\,\mathrm{eV} \quad \Rightarrow \quad \eta_B^{\max} = 10^{-2}\, \dfrac{3}{16\pi}\, \dfrac{M_1 m_{\nu_3}}{v^2}\, \kappa$



$\Rightarrow$ Lower bound on the baryogenesis temperature

$T_B \sim M_1 \gtrsim 10^9\,\mathrm{GeV}$

$t_B \sim 10^{-25}\,\mathrm{s}$

Constraints on neutrino parameters

1. N_1 production processes $\propto \widetilde{m}_1 \Rightarrow$ lower limit on $\widetilde{m}_1$
2. Washout processes:

   res. contrib. from $N_1 \propto \widetilde{m}_1 \Rightarrow$ upper limit on $\widetilde{m}_1$

   remainder $\propto M_1 \overline{m}^2 \Rightarrow$ upper limit on M_1 for fixed $\overline{m}$
3. maximal CP asymmetry $\propto M_1 \Rightarrow$ lower limit on M_1
   since $\eta_B \propto \varepsilon_1$

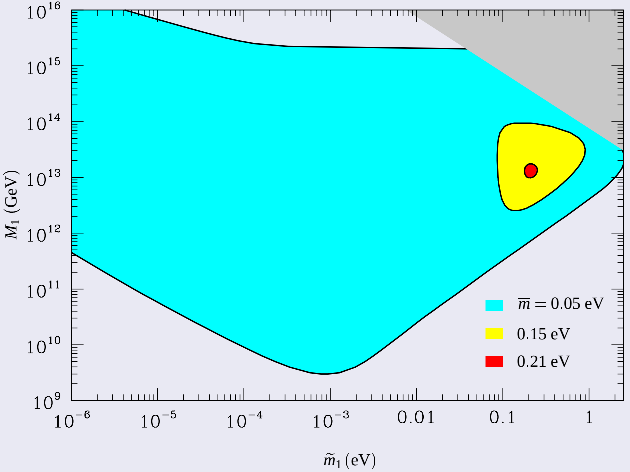
for fixed $\overline{m} \Rightarrow$ allowed region in $(\widetilde{m}_1, M_1)$ plane

Size of allowed region depends on $\overline{m}$ since:

- max. CP asymm. suppressed for quasi-degenerate light νs
- $\widetilde{m}_1 \geq m_{\nu_1}$

$\Rightarrow$ upper bound on $\overline{m}$

(Buchmüller, Di Bari & M.P. ’03, ’04)



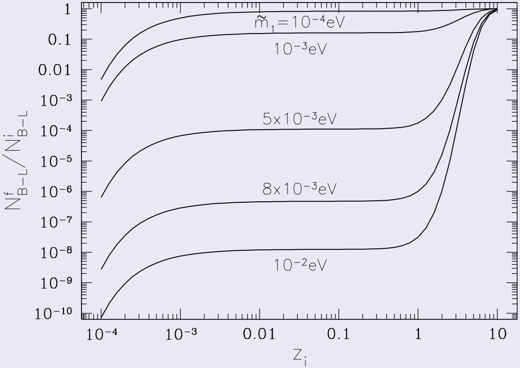
light ν masses: $\overline{m} < 0.22\,\mathrm{eV} \quad \Rightarrow \quad m_{\nu_i} < 0.13\,\mathrm{eV}$

RHN masses: $T_B \sim M_1 \gtrsim 10^9\,\mathrm{GeV}$

How robust are these bounds???

Initial conditions: Primordial Asymmetry?

initial asymmetry before leptogenesis:
effect of washout?



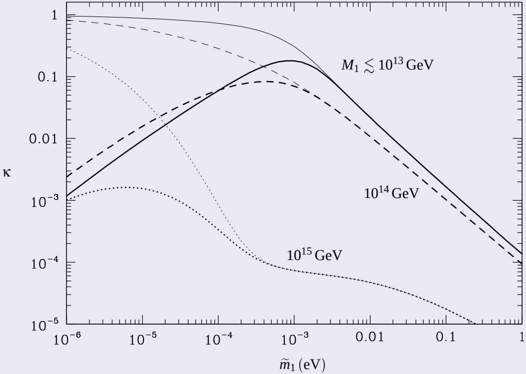
Washout factor for hierarchical light νs: $\overline{m} = 0.05\,$eV and $M_1 = 10^{10}\,$GeV

Initial temperature: $z_i = \dfrac{M_1}{T_i}$

efficient washout of initial asymmetry at $z_i \sim 1$ for $\tilde{m}_1 \gtrsim 10^{-3}\,$eV

no dependence on initial conditions for $\tilde{m}_1 \gtrsim 5 \times 10^{-3}\,$eV

Initial conditions: Neutrino production?



hierarchical light νs: $\overline{m} = 0.05\,$eV

initial conditions

- $N_{N_1} = N_{N_1}^{\rm eq}$ at $T \gg M_1$: thin lines
- $N_{N_1} = 0$ at $T \gg M_1$: thick lines

no dependence on initial conditions for $\widetilde{m}_1 \gtrsim 10^{-3}\,$eV

The neutrino mass window for baryogenesis

- upper bound on light ν masses $m_{\nu_i} \lesssim 0.1\,\mathrm{eV}$
- no dependence on initial conditions for $\widetilde{m}_1 \gtrsim 10^{-3}\,\mathrm{eV}$

since $\widetilde{m}_1 \geq m_{\nu_1} \rightarrow$ leptogenesis window for neutrino masses

$$10^{-3}\,\mathrm{eV} \lesssim m_{\nu_i} \lesssim 0.1\,\mathrm{eV}$$

compatible with ν oscillations $(m_{\mathrm{atm}} \sim 0.05\,\mathrm{eV})$

Analytical solution for efficiency factor in leptogenesis window:

$$\kappa = (2 \pm 1) \times 10^{-2} \left(\frac{0.01\,\mathrm{eV}}{\widetilde{m}_1} \right)^{1.1 \pm 0.1}$$

How reliable are those results?

The neutrino mass window for baryogenesis

- upper bound on light ν masses $m_{\nu_i} \lesssim 0.1\,\mathrm{eV}$
- no dependence on initial conditions for $\widetilde{m}_1 \gtrsim 10^{-3}\,\mathrm{eV}$

since $\widetilde{m}_1 \geq m_{\nu_1} \to$ leptogenesis window for neutrino masses

$$10^{-3}\,\mathrm{eV} \lesssim m_{\nu_i} \lesssim 0.1\,\mathrm{eV}$$

compatible with ν oscillations $(m_{\mathrm{atm}} \sim 0.05\,\mathrm{eV})$

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Kinetic vs. thermal equilibrium

Lower limit on M_1 from weak washout regime $(\widetilde{m}_1 \ll 10^{-3}\ \mathrm{eV})$

$\rightarrow$ strong dependence on initial conditions and on how system approaches thermal equilibrium

Usual calculations rely on approximations:

1. Maxwell-Boltzmann statistics
2. Kinetic equilibrium: $f(E) = \frac{n}{n^{\mathrm{eq}}} \mathrm{e}^{-E/T}$

Scattering cross sections are energy-dependent, i.e. assuming kinetic equilibrium seems questionable.

Need to study how the system approaches equilibrium and how that depends on different assumptions (with F. Hahn-Woernle).

Thermal corrections

Leptogenesis takes place in a thermal bath

$\longrightarrow$Thermal corrections have to be considered, should regulate IR divergences

Controversial results, based on high temperature approximations, in literature (Covi et al., '98; Giudice et al., '03)

Need to compute scattering and decay rates in finite temperature field theory (with C. Kiessig and F. Steffen)

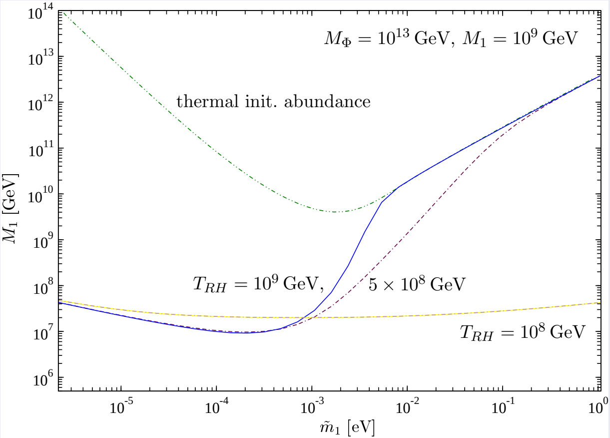
Problem: two limiting cases considered in literature

1. thermal corrections for heavy states, i.e. $T \ll M$
2. thermal effects for massless fields, i.e. $T \gg M$

Relevant regime for leptogenesis: $T \sim M$

Non-thermal leptogenesis (with F. Hahn-Woernle)

Assume: N_1 produced in inflaton decays, not thermally



Lower bound on M_1 relaxed by several orders of magnitude!

Experimental consequences of leptogenesis?

- Upper bound on light neutrino masses: endpoint of electron spectrum in tritium beta decay $\longrightarrow$ Katrin
- Neutrinos are Majorana particles $\Rightarrow$ Neutrinoless double beta decay $\longrightarrow$ Gerda et al.
- CP violation in neutrino oscillations: detectable in long baseline experiments if θ_{13} not too small $\longrightarrow$ Double Chooz and Daya Bay

Origin of normal matter understood!?

Conclusions

Leptogenesis relates the cosmological baryon asymmetry to properties of light neutrinos:

- Quasi-degenerate light ν masses are incompatible with η_B:

$$m_{\nu_i} \lesssim 0.1\ \mathrm{eV}$$

- lower bound on the baryogenesis temperature:

$$T_B \gtrsim 10^9\ \mathrm{GeV}\,, \qquad t_B \sim 10^{-25}\,\mathrm{s}$$

- leptogenesis works best in neutrino mass window

$$10^{-3}\,\mathrm{eV} \lesssim m_{\nu_i} \lesssim 0.1\,\mathrm{eV}$$

consistent with neutrino oscillations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How does a violation of CP arise?

Consider a simple example, e.g. the decay of a particle X into some final state f and the CP conjugated process $\overline{X} \to \overline{f}$

Generic amplitude at tree level and one-loop:

$$A(X \to f) = g_0 A_0 + g_1 A_1$$

Decay width at LO (tree level) and NLO (interference between tree level and one-loop):

$$\Gamma(X \to f) = |g_0|^2 I_0 + g_0 g_1^* I_1 + g_0^* g_1 I_1^*$$

$g_{0,1}$: (products of) coupling constant(s) at tree level and 1-loop
$I_{0,1}$: kinematical factors at LO and NLO (phase space, etc.)
$\rightarrow$ identical for particles and anti-particles (CPT)

CP conjugated process:

$$\Gamma(\overline{X} \to \overline{f}) = |g_0|^2 I_0 + g_0^* g_1 I_1 + g_0 g_1^* I_1^*$$

CP asymmetry:

Diference of decay widths:

$$\begin{aligned}\varepsilon &\propto \Gamma(X \to f) - \Gamma(\overline{X} \to \overline{f}) \\ &= g_0 g_1^* I_1 + g_0^* g_1 I_1^* - g_0^* g_1 I_1 - g_0 g_1^* I_1^* \\ &= (g_0 g_1^* - g_0^* g_1)(I_1 - I_1^*) \\ &= -4\,\mathrm{Im}\,(g_0 g_1^*)\,\mathrm{Im}\,(I_1)\end{aligned}$$

Two different phases are needed in order to get CP violation:

1. one phase from the couplings
2. one phase from the kinematical factors: rescattering phase, arises if particles in loop are on-shell

Alternatives?

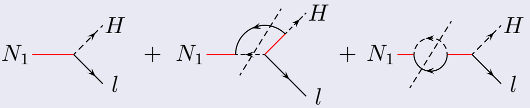
What if light neutrinos are quasi-degenerate?

What if the reheating temperature is lower than $\sim 10^9$ GeV?

- decouple light neutrino masses from baryogenesis, i.e. contribution to light ν masses and/or baryogenesis from triplet Higgs
  some other mechanism for light ν masses,...
- resonant leptogenesis, soft leptogenesis in SUSY models
- flavour effects
- non-thermal leptogenesis, i.e. through inflaton decay or Affleck-Dine, ...

Resonant Leptogenesis

Resonant enhancement of CP-asymmetry for $M_{2,3} - M_1 \ll M_1$:



Almost no effect on bound on light ν masses, but lower limit on T_B, M_1 can be relaxed.

However: many different results in literature !?

Problem: N_i unstable, i.e. cannot appear as in- or out-states of S-matrix elements

Solution: scattering amplitudes of stable particles with N_i as intermediate states

Factorisation: effective one-loop couplings of N_i

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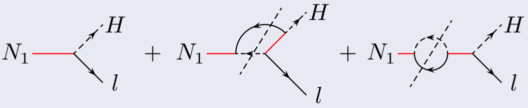

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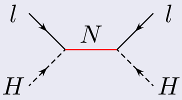

Factorisation: effective one-loop couplings of N_i

Resummation of self-energies

regularizes resonant propagator $\Rightarrow$ mixing effects

$$\left(S^{-1}\right)_{ij} = \not{p} - M_i - \Sigma_{ij}$$

Renormalization known (Kniehl & Pilaftsis '96)

Chiral decomposition of propagator:

$$S = P_R S^{RR} + P_L S^{LL} + P_L \not{p} S^{LR} + P_R \not{p} S^{RL}$$

Contribute to different scattering processes:

$$\mathscr{M}(l_r \to \bar{l}_s) \propto h_{ri} S_{ij}^{LL} h_{sj} \qquad \mathscr{M}(\bar{l}_r \to l_s) \propto h_{ri}^* S_{ij}^{RR} h_{sj}^*$$

$$\mathscr{M}(l_r \to l_s) \propto h_{ri}^* S_{ij}^{RL} h_{sj} \qquad \mathscr{M}(\bar{l}_r \to \bar{l}_s) \propto h_{ri} S_{ij}^{LR} h_{sj}^*$$

Contributions of different N_i mass eigenstates?

Factorization (Anisimov, Broncano & M.P. '05):

Different methods:

1. Decompose scattering ampl. into partial fractions, e.g.:

$$\mathcal{M}(l_r \to \bar{l}_s) \propto \lambda_{r1} \frac{1}{p^2 - \hat{M}_1^2} \lambda_{s1} + \lambda_{r2} \frac{1}{p^2 - \hat{M}_2^2} \lambda_{s2} + \dots$$

   λ_{ri}: resummed effective N_i Yukawa coupling

   Consistency: all 4 amplitudes can be factorized simultaneously.

2. Diagonalization of propagators, e.g.: $U S^{LL} U^T = S^{\text{diag}}$

$$\mathcal{M}(l_r \to \bar{l}_s) \propto \left(hU^T\right)_{ri} S_{ii}^{\text{diag}} \left(hU^T\right)_{si}$$

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Results:

Both methods yield identical results for physical quantities:

1. Decay widths: $\Gamma(N_i \to \bar{l}_r) \propto |\lambda_{ri}|^2 = \left|\left(hU^T\right)_{ri}\right|^2$, for $p^2 = M_i^2$
2. CP-asymmetries, e.g.:

$$\varepsilon_1 \propto \frac{M_2^2 - M_1^2}{\left(M_2^2 - M_1^2\right)^2 + \left(M_2\Gamma_2 - M_1\Gamma_1\right)^2} ,$$

Previous approaches, e.g., resum only self-energy Σ_{jj} of intermediate neutrino $N_j \Rightarrow$ regulator: Γ_j (Pilaftsis & Underwood '04)

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Different neutrino flavours are treated differently!

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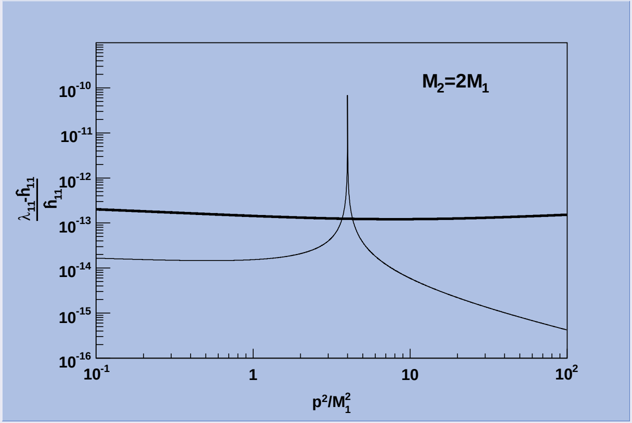
Relative one-loop correction to couplings of N_1

Our result (thick line) compared to the one of Pilaftsis et al.:



thin line has resonance at $p^2 = M_2^2$, i.e. contributions from different neutrino mass eigenstates not properly separated in previous approaches.

Type I Seesaw: introduce right-handed neutrinos N

Lepton Yukawa couplings: $\mathscr{L}_Y = \overline{E}\lambda_l lH + \overline{N}\lambda_\nu lH - \frac{1}{2}\overline{N}MN$

Dirac masses $m_l = \lambda_l v$ and $m_\mathrm{D} = \lambda_\nu v$

$\rightarrow \nu$ mass matrix: $\begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix}$

natural assumption: $M \gg m_\mathrm{D}$

First prediction: 6 neutrino Majorana mass eigenstates

N	with	$m_N \simeq M$
ν	with	$m_\nu \simeq -m_\mathrm{D}\frac{1}{M}m_\mathrm{D}^T = \mathscr{O}\left(\frac{v^2}{M}\right)$

$v \sim 100\,$GeV: SM mass scale; M: mass of N.

Return