Baryon asymmetry of the Universe

from

sterile neutrinos

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Outline

baryon asymmetry of the Universe from neutrinos: leptogenesis

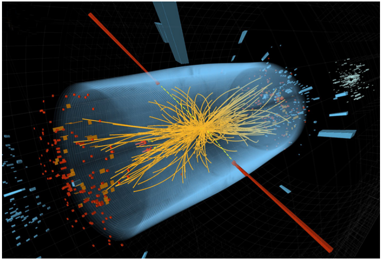
first principle approach: effective equations of motion

coefficients from thermal Green's functions: washout

production of ultrarelativistic sterile neutrinos

Physics beyond the Standard Model

all particles of the SM have been found



physics beyond beyond the SM must account for

- dark matter particles
- neutrino masses
- baryon asymmetry

Baryon asymmetry of the Universe (BAU)

net baryon density

$n_B \equiv n_b - n_{\overline{b}}$

baryon to photon ratio

$\eta \equiv n_B / n_\gamma$

Big Bang Nucleosynthesis

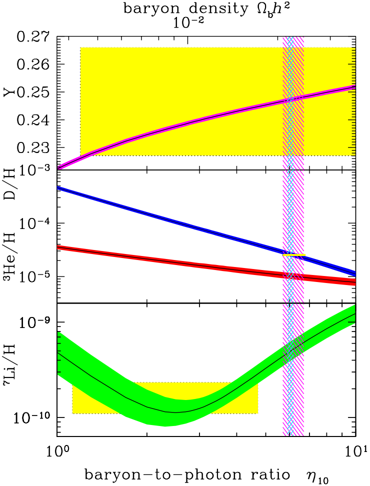
(1 MeV $\gtrsim T \gtrsim$ 10 keV) $\rightsquigarrow$

$5.7 < (\eta \times 10^{10}) < 6.7$

Cosmic Microwave Background

($T \sim$ 0.25 eV)

$\eta \times 10^{10} = 6.04 \pm 0.08$ [Planck]



[Particle Data Group]

Baryon asymmetry of the Universe (BAU)

why is $\eta \neq 0$?

initial condition?

not if there was inflation!

Sakharov: asymmetry can be dynamically generated if there is

1. baryon number violation
2. C and CP violation
3. non-equilbrium

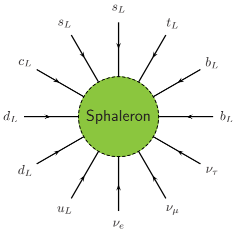
Baryon + lepton number violation

$B - L$ is conserved in the Standard Model

$B + L$ is not [t'Hooft]

$B + L$ violation unsuppressed for $T \gtrsim$ **160 GeV**

'sphaleron' processes



Lepton asymmetry $\leftrightarrow$ Baryon asymmetry

Neutrino masses

SM: massless neutrinos, but from neutrino oscillations:

$\Delta m^2_{\text{solar}} \simeq 7.6 \times 10^{-5}$eV, $\quad \Delta m^2_{\text{atmospheric}} \simeq 2.4 \times 10^{-3}$eV

add right-handed (sterile) neutrinos $N_I = N_I^c$:

$$\mathscr{L}_N = \frac{i}{2}\overline{N}\not\partial N - \frac{1}{2}\overline{N^c}MN - \left(\overline{N}h\widetilde{\varphi}^\dagger \ell + \text{ h.c. }\right)$$

$M \gg hv \Rightarrow$ see-saw formula for light ν mass matrix

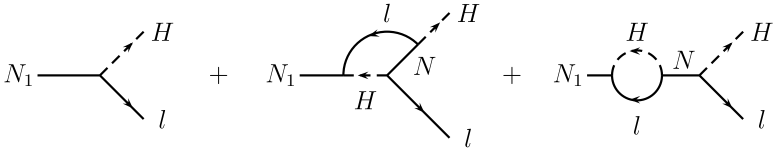
$$m_\nu = hM^{-1}h^Tv^2$$

$m_\nu \sim$ 0.1 eV,
$m_e/v < h < 1 \Leftrightarrow$
TeV $\lesssim M \lesssim M_{\text{GUT}}$

Baryogenesis through leptogenesis [Fukugita, Yanagida]

Majorana masses M_{ij} → lepton number violation

complex Yukawa couplings h_{ij} → CP-violation



decay rates

$$\Gamma(N \to \ell\varphi) \neq \Gamma(N \to \bar{\ell}\bar{\varphi})$$

$\Gamma \lesssim H$ → non-equilibrium

Baryogenesis through leptogenesis: scenarios

thermal leptogenesis (non-resonant)

- asymmetry from sterile neutrino **decay**
- no fine tuning
- close to thermal equilibrium, non-relativistic [DB, Wörmann]
- lightest sterile neutrino $M_1 \gtrsim 10^9$ GeV [Davidson, Ibarra; di Bari]
- GUT scale physics

resonant leptogenesis: $M_2 - M_1 \sim$ thermal width [Pilaftsis, Underwood]

- no mass bound

Baryogenesis through leptogenesis: scenarios

asymmetry from **production** of sterile N_i [Akhmedov, Smirnov, Rubakov]

- far from equilibrium
- M_2, $M_3 \gtrsim$ MeV [Canetti, Drewes, Shaposhnikov '13]
- thermal effects $\rightarrow$ no fine tuned mass degeneracy needed

[Drewes, Garbrecht]

Decay and non-equilibrium

$$K \equiv \left.\frac{\Gamma_0}{H}\right|_{T=M_1} \quad \text{'washout factor'}$$

$K \gg 1$: close to equilibrium when $T \sim M_1$ 'strong washout'

$K \ll 1$: far from equilibrium when $T \sim M_1$ 'weak washout'

$$K = \frac{\widetilde{m}_1}{m_*}, \qquad \widetilde{m}_1 = \frac{(m_D m_D^\dagger)_{11}}{M_1} \qquad m_* \simeq 10^{-3}\ \text{eV}$$

$\widetilde{m}_1 >$ smallest light neutrino mass [Fujii, Hamaguchi, Yanagida]

$$(\Delta m^2_{\text{solar}})^{1/2} < \widetilde{m}_1 < (\Delta m^2_{\text{atmospheric}})^{1/2} \quad \Leftrightarrow \quad 7.4 < K < 46$$

Traditional approach to leptogenesis

Boltzmann equations for phase space densities $f_a(t, |\mathbf{p}|)$

$$D_t f_a = \text{Coll}_a[f]$$

collision term (for leptons)

$$\text{Coll}_\ell[f] = \int_{\mathbf{p}_i} (2\pi)^4 \delta(p_\ell + p_{\overline{\varphi}} - p_N)$$
$$\times \left[|\mathcal{M}|^2_{N\to\ell\overline{\varphi}} f_N (1 - f_\ell)(1 + f_{\overline{\phi}}) - |\mathcal{M}|^2_{\ell\overline{\varphi}\to N} f_\ell f_{\overline{\varphi}} (1 - f_N) \right] + \cdots$$

problems:

- double counting of resonant intermediate states
- unclear how to include medium effects
- theoretical error $\leftrightarrow$ radiative corrections ???

First principles approaches to leptogenesis

identify slow and fast variables X

$\gamma_X =$ relaxation rate

$\gamma_X \gg H$ fast, in thermal equilibrium *spectator processes*

$\gamma_X \sim H$, slow, interesting non-equilibrium dynamics

$\gamma_X \ll H$ practically conserved

write effective equations of motion for slow ones

computation = 'two step procedure'

1. short time/distance physics $\rightsquigarrow$ coefficients
2. solve effective equations of motion

[DB, M. Laine, M. Sangel, M. Wörmann]

First principles approaches to leptogenesis

effective equations of motion for slow variables

$$D_t X_a = -\gamma_{ab} X_b$$

valid

- on time scales $\gtrsim \gamma^{-1}$
- to all orders in Standard Model couplings

coefficients

$$\gamma_{ab} = \gamma_{ab}(T)$$

- determined by short time physics
- only depend on temperature
- radiative corrections can be systematically computed

Non-relativistic unflavored leptogenesis

non-relativistic approximation: neglect motion of N_i

Simplest case:

$M_1 \ll M_2, M_3$

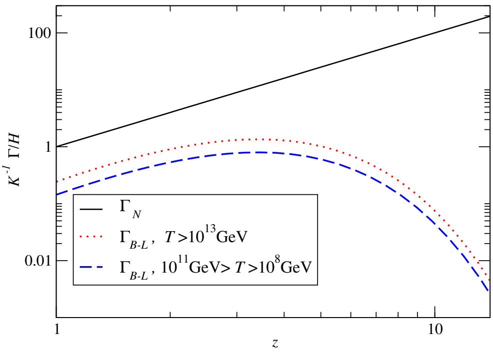
only one charged lepton flavor relevant

$\rightsquigarrow$ only $n_N \equiv n_{N_1}$ and n_{B-L} need to be considered

$$\left(\frac{d}{dt} + 3H\right) n_{_N} = -\gamma_{_N} \left(n_{_N} - n_{_{N,eq}}\right) + \gamma_{_{N,B-L}}\, n_{_{B-L}}$$

$$\left(\frac{d}{dt} + 3H\right) n_{_{B-L}} = \gamma_{_{B-L,N}} \left(n_{_N} - n_{_{N,eq}}\right) - \gamma_{_{B-L}}\, n_{_{B-L}}$$

Rates vs $z \equiv M_1/T$



n_N approaches equilibrium

exponentially small for $T \ll M_1$

l'genesis must happen before

$B-L$ washout rate γ_{B-L}

maximal for $z \sim 4$

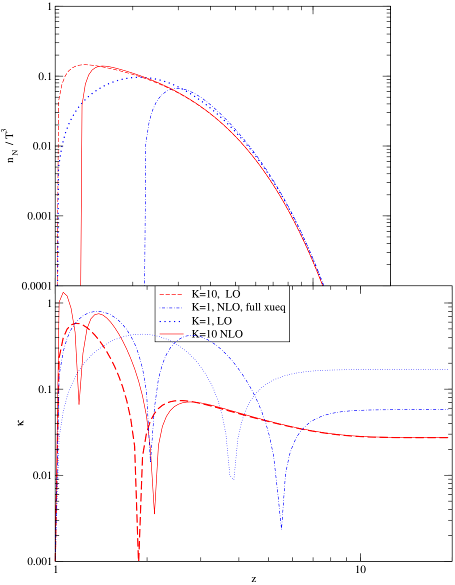
$\to 0$ for $z \to \infty$

asymmetry freezes in

[DB, M. Wörmann]

$$K \equiv \left. \frac{\Gamma_0}{H} \right|_{T=M_1} \quad \text{'washout factor'}$$

Non-relativistic, relativistic corrections



relativistic correction:

include also kinetic energy density of sterile N

γ_{ab} from correlation of thermal fluctuations

[DB, M. Laine]

effective eqs. of motion for thermal fluctuations

$$\dot{X}_a = -\gamma_{ab} X_b + \xi_a$$

Langevin equation

random force ξ

$$\langle \xi_a(t) \xi_b(t') \rangle \propto \delta(t - t')$$

real time correlation function

$$\langle X_a(t) X_c(0) \rangle = (e^{-\gamma t})_{ab} \langle X_b X_c \rangle$$

Correlations from finite temperature QFT

$$C_{ab}(t) \equiv \frac{1}{2} \langle \{ X_a(t), X_b(0) \} \rangle$$

match results at time/frequency scales

$$t_{\rm UV} \ll t \ll \gamma^{-1}, \qquad \omega_{\rm UV} \gg \omega \gg \gamma$$

at leading order in h:

$$\gamma_{ab} = \frac{1}{2V} \lim_{\omega \to 0} \frac{1}{\omega} \int {\rm d}t \, e^{i\omega t} \left\langle \left[\dot{X}_a(t), \dot{X}_c(0) \right] \right\rangle_0 \left(\Xi^{-1} \right)_{cb}$$

similar to Kubo relation for transport coefficients:
viscosity, in particular diffusion constants

matrix of susceptibilities $\qquad \Xi_{ab} \equiv \dfrac{1}{TV} \langle X_a X_b \rangle$

Washout rate

$$\left(\frac{d}{dt} + 3H\right) n_{_N} = -\gamma_{_N} \left(n_{_N} - n_{_{N,eq}}\right) + \gamma_{_{N,B-L}}\, n_{_{B-L}}$$

$$\left(\frac{d}{dt} + 3H\right) n_{_{B-L}} = \gamma_{_{B-L,N}} \left(n_{_N} - n_{_{N,eq}}\right) - \gamma_{_{B-L}}\, n_{_{B-L}}$$

Washout rate

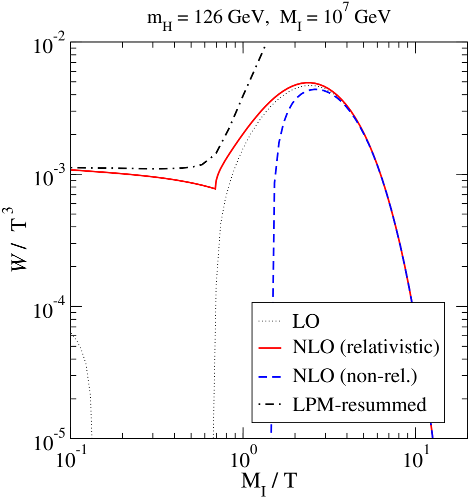
integrate out N_I at leading order $\Rightarrow$

$$\gamma_{ab} = -\frac{1}{2}\sum_I \int_{\mathbf{k}} \frac{f'_{\rm F}(E_I)}{2E_I}\, h_{Ii}\ \mathsf{tr}\Big[\not{k}\Big(T^\ell_a\big[\,\widetilde{\rho}(k)+\widetilde{\rho}(-k)\,\big]T^\ell_c + T^\ell_c\big[\,\widetilde{\rho}(k)+\widetilde{\rho}(-k)\,\big]T^\ell_a\Big)_{ij}\Big]h^*_{Ij}\,\big(\Xi^{-1}\big)_{cb}$$

with spectral function

$$\widetilde{\rho}_{ij\alpha\beta}(k) \equiv \int_x e^{ik\cdot x}\Big\langle \Big\{(\widetilde{\varphi}^\dagger \ell_{i\alpha})(x), (\overline{\ell}_{j\beta}\,\widetilde{\varphi})(0)\Big\}\Big\rangle_0$$

Washout rate



integral over spectral function

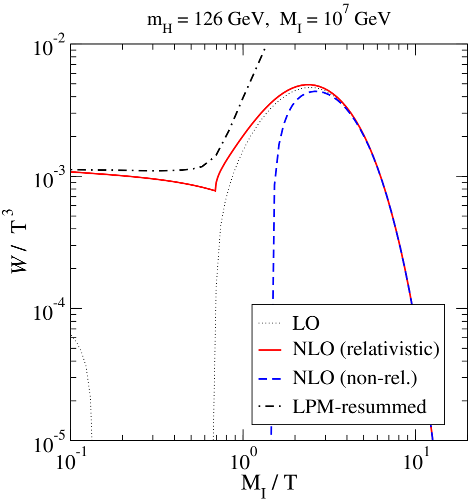
spectral function results

ultra-relativistic ($M_I \lesssim g^2 T$):
complete LO [D Besak, DB]

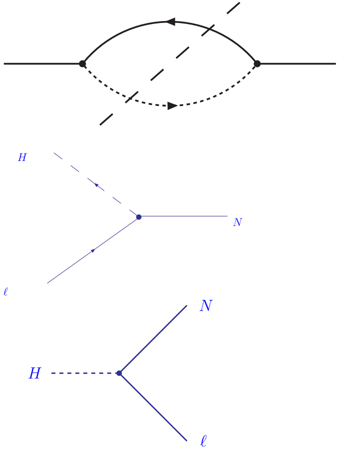
relativistic ($M_I \sim T$):
NLO [M Laine]

non-relativistic ($M_I \gg T$):
NLO
[A Salvio et al., Laine, Y Schröder]

Washout rate

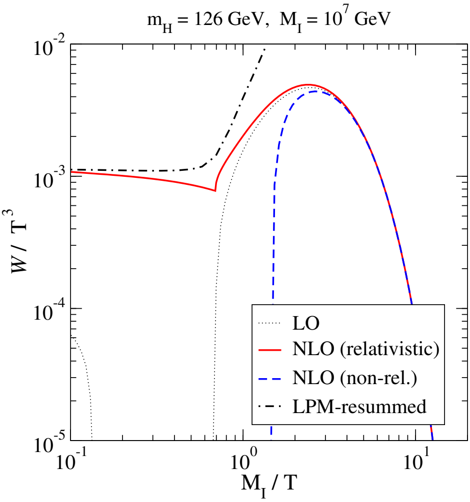


(naive) LO

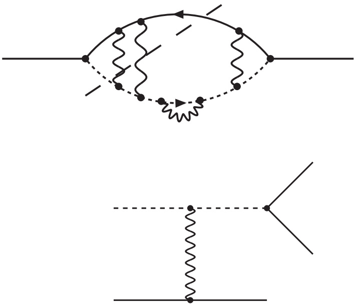


integral over spectral function

Washout rate



complete LO



integral over spectral function

Washout rate

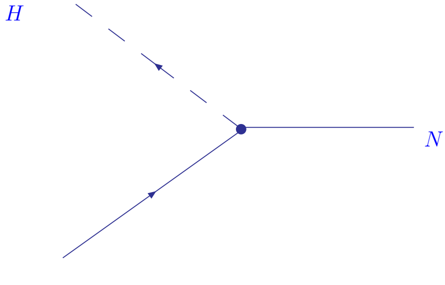
corrections to spectral functions (non-relativistic and relativistic) $= O(g^2)$

corrections to susceptibilities $= O(g)$, infrared effect

leading corrections from 'simple' thermodynamics

complete $O(g^2)$ computed [DB, M. Sangel]
corrections $\leq 4\%$, mostly from QCD

N-production: inverse decay



H = Higgs

ℓ = Standard Model lepton

momenta $= O(T)$

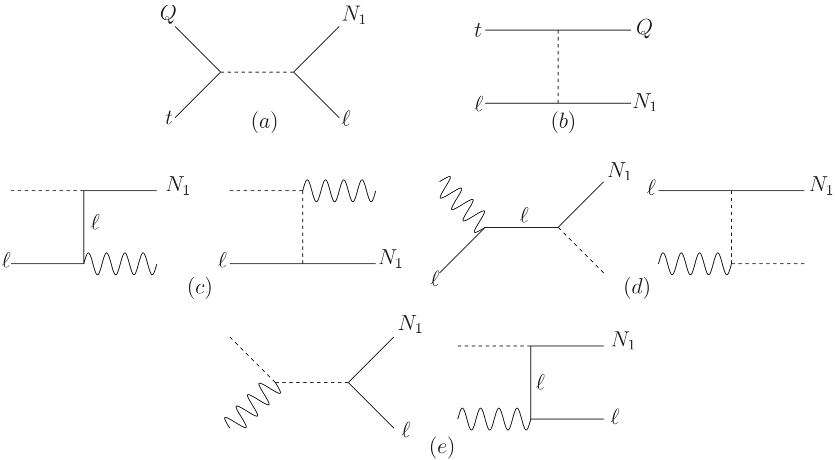
at high temperature $T \gtrsim M_N$:
momenta are

close to light cone

nearly collinear

when $M_N \lesssim gT$:
- opening angle $= O(g)$ '
- $O(g^2)$ phase space suppression

N-production: $2 \to 2$ scattering

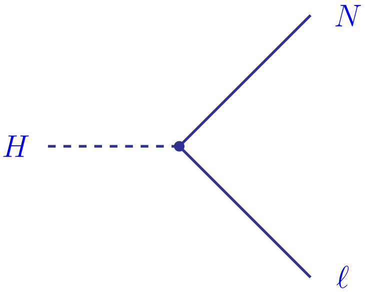


Besak, DB

Thermal mass effects

medium effects $\rightsquigarrow$ thermal masses

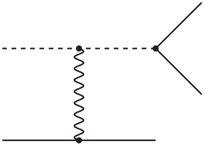
$\rightsquigarrow$ new channel



opening angle $= O(g)$ '

leading order contribution

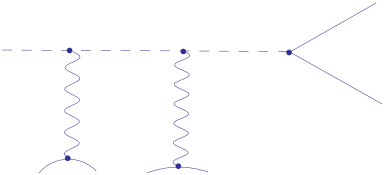
Soft gauge interactions



collinear enhancement

compensates additional vertices

$\rightsquigarrow$ leading order contribution



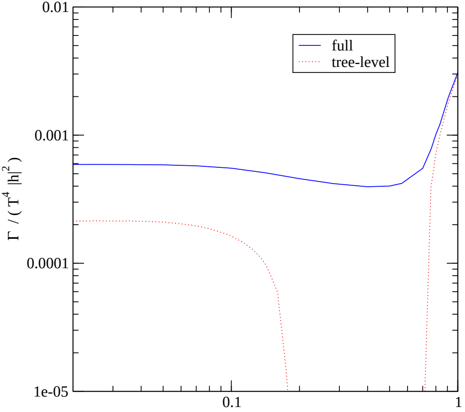
multiple soft scattering unsuppressed

leading order contribution

Landau-Pomeranchuk-Migdal effect

[Anisimov, Besak, DB]

Thermal masses + soft gauge interactions



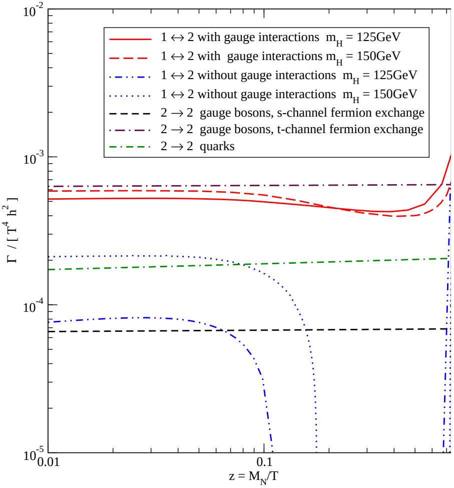
soft gauge interactions

⇝

factor 3 enhancement

at high T

Complete LO production rate



gauge interactions

dominate

Summary and outlook

lot of theoretical progress in leptogenesis

systematic approach by identifying fast, slow and quasi-static quantities

effective equations of motion for slow quantities

coefficients in effective equations of motion related to real time correlation functions at finite temperature

Kubo-type relatons, valid to all orders in Standard Model couplings

NLO and NNLO corrections computed for washout rate

thermal production of ultrareltivistic N: thermal mass effects, soft gauge interactions very important

Outlook

CP-asymmetry ?

error bars for leptogenesis

CP asymmetry in ultrarelativistic regime