LEPTOGENESIS

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Leptogenesis

Contents

Leptogenesis

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1])

The question of baryogenesis can in principle be answered by particle physics/quantum field theory & cosmology because these can satisfy the Sakharov conditions:

(1) baryon number B violation
(2) charge C and charge-parity CP violation
(3) deviation from thermodynamic equilibrium

Baryogenesis at 60

(C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

2

1

We assume that the baryon and muon conservation laws are not absolute and should be

energy densities were n ~ 10 cm and ε ~ 10 erg/cm).

M. A. Markov (see [5]) proposed that during the early stages there existed particles with maximum mass on the order of one gravitational unit ($M_0 = 2 \times 10^{-5}$ g in ordinary units), and called them maximons. The presence of such particles leads unavoidably to strong violation of thermodynamic equilibrium. We can visualize that neutral spinless maximons (or

3

The question of baryogenesis can in principle be answered by particle physics/quantum field theory & cosmology because these can satisfy the Sakharov conditions:

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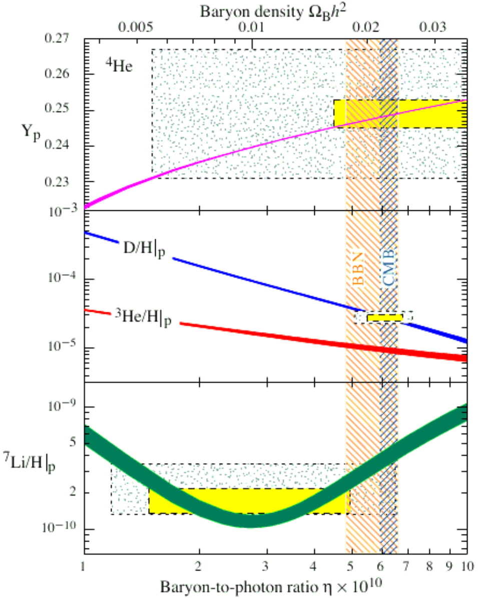
BAU measurements – BBN (big bang nucleosynthesis)



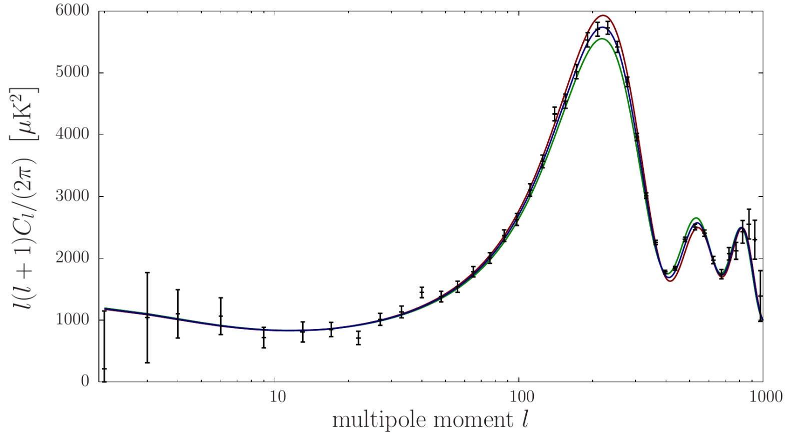
$$\eta_B = \frac{n_B}{n_\gamma} = (5.1\text{–}6.5) \times 10^{-10}$$

@ 95% c.l.

Baryon-to-photon ratio $\eta_B = \dfrac{n_B}{n_\gamma}$ is conserved after electrons and positrons annihilate

At high (relativistic) temperatures:
$n_\gamma \sim$ number density of particles
$\sim$ entropy density s

One excess particle for $\sim 10^{10}$ particle-antiparticle pairs



baryon acoustic oscillations

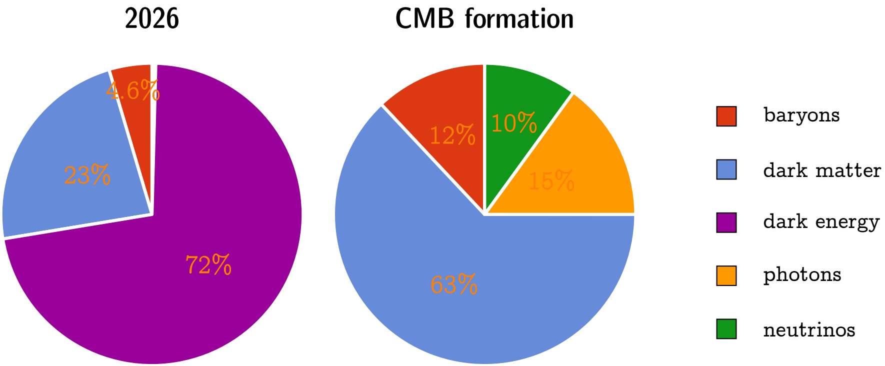
Quantitative agreement between BBN & CMB a success of applying particle/nuclear physics to cosmology

— η_B — $\eta_B + 10\%$ — $\eta_B - 10\%$ $(\langle a_{\ell m} a^*_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'} C_\ell)$

First peak (roughly) corresponds to sound horizon at the time of CMB formation.

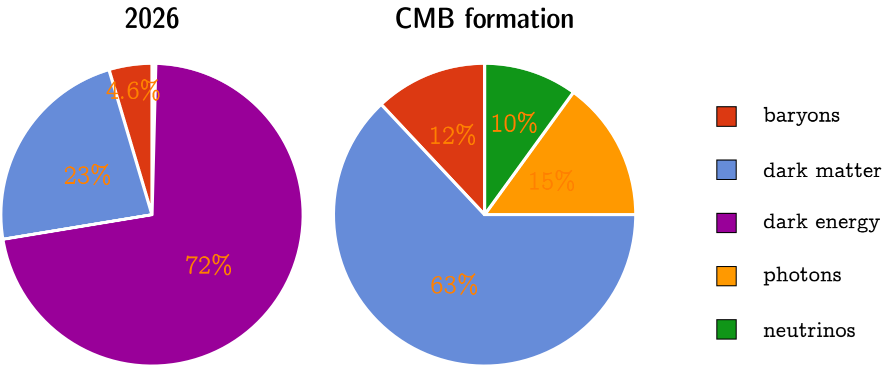
$$\eta_B = \frac{n_B}{n_\gamma} = (6.15 \pm 0.15) \times 10^{-10}$$

Cosmic pie



Overview adapted from A. Ritz

dark matter	neutrinos	baryons
relic abundance	relic abundance	relic abundance
identity	identity ν mass	identity
DM genesis	neutrino production	baryogenesis
asymmetry	lepton asymmetry	asymmetry



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relic abundance ✓	relic abundance ✓	relic abundance ✓
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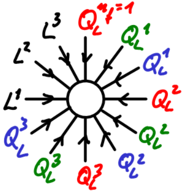
DM genesis ?	neutrino production ✓	baryogenesis ?
asymmetry ?	lepton asymmetry ?	asymmetry ✓

Check Sakharov conditions:

1. B violated due to anomalous $B+L$ violation via sphaleron processes
2. CP violation in CKM matrix, C and P violation in weak interactions
3. Deviation from equilibrium due to expansion of the Universe



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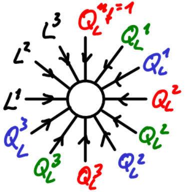

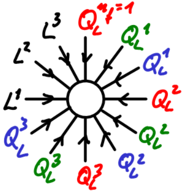

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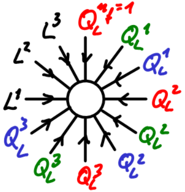
However, conditions for baryogenesis not met **quantitatively**:

- CP rephasing invariant normalised to electroweak scale is tiny:
  $\mathrm{Im}\left[\det[m_u m_u^\dagger, m_d m_d^\dagger]\right] \approx -2Jm_t^4 m_b^4 m_c^2 m_s^2$, $J \approx 3 \times 10^{-5}$,
  $2J\frac{m_t^4 m_b^4 m_c^2 m_s^2}{T^{12}} \approx 3 \times 10^{-19}$ for $T = 100\,\mathrm{GeV}$.
- Deviation from equilibrium $H/\Gamma \sim (T^2/m_{\mathrm{Pl}})/(g^4 T) = g^{-4} T/m_{\mathrm{Pl}}$ with $g = \mathcal{O}(1)$ is tiny unless T is very high ($m_{\mathrm{Pl}} = 1.2 \times 10^{19}\,\mathrm{GeV}$).
  Loophole: For $m_H < 70\mathrm{GeV}$, first order phase transition [Kajantie, Laine, Rummukainen, Shaposhnikov (1996)]. Ruled out by discovery $m_H = 125\mathrm{GeV}$. Still possible beyond the SM when light bosons couple to the Higgs field.

Situation in the Standard Model (SM)



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Baryogenesis requires physics beyond the Standard Model.

Contents

Leptogenesis

Most minimal extension (?)

To have baryogenesis, extend the SM by:

- Gauge singlet ($\rightarrow$ deviation from equilbrium)
- Couples at renormalizable level
- Does not simply decay into particle/antiparticle pairs

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$\rightarrow$ **Right-handed neutrino (RHN)** N

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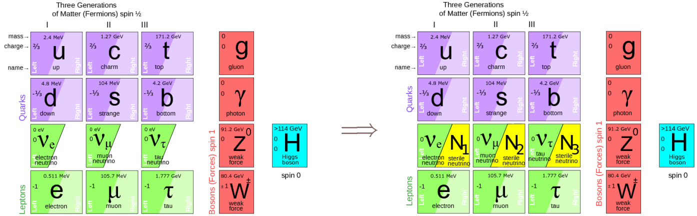
$\to$ **Right-handed neutrino (RHN) N**



[Figure: Gninenko, Gorbunov, Shaposhnikov (2013)]

Assume here for simplicity one left-handed ν and one RHN with Majorana mass M

Yukawa coupling $Y\bar{\nu}\phi^0 N \xRightarrow{\langle\phi^0\rangle = v = 174\text{GeV}}$ Dirac mass $m_D = Yv$ $\;(H \equiv \phi$ Higgs field$)$ $\longrightarrow$

Mixing mass matrix: $\frac{1}{2}(\bar{\nu}\;\bar{N}^c)\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu^c \\ N \end{pmatrix}$ where $M \gg m_D \quad \longrightarrow$

Eigenvalues: $\left\{\frac{1}{2}\left(M \mp \sqrt{M^2 + 4m_D^2}\right)\right\} \approx \left\{M, m_D^2/M\right\} = \left\{M, Y^2v^2/M\right\} \;\to m = Y^2v^2/M$

Eigenvectors: $\begin{pmatrix} \nu^{\text{light}} \\ \nu^{\text{heavy}\;c} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} \nu \\ N^c \end{pmatrix}$ where $\theta = m_D/M + \mathcal{O}\left(\frac{m_D^3}{M^3}\right)$

Bonus: **neutrino masses**

Type-I seesaw mechanism

[P. Minkowski (1977); Gell-Mann, Ramond, Slansky (1979)]

CP violation & quantum interference

Squared amplitude for some CP violating process:

$$\left| a_1 \cdots a_m |\mathcal{A}_a| \mathrm{e}^{\mathrm{i}\varphi_a} + b_1 \cdots b_n |\mathcal{A}_b| \mathrm{e}^{\mathrm{i}\varphi_b} \right|^2 \underset{\times\text{-term}}{\supset} (a_1 \cdots a_m b_1^* \cdots b_m^* \mathrm{e}^{\mathrm{i}(\varphi_a - \varphi_b)} + \text{c.c.}) |\mathcal{A}_a \mathcal{A}_b|$$

a_i, b_i: coupling constants

$\arg(a_1 \cdots a_m b_1^* \cdots b_m^*)$: CP odd phase

$\mathcal{A}_{a,b}$: amplitudes stripped of coupling constants

$\varphi_{a,b}$: (CP even) phases of $\mathcal{A}_{a,b}$,

Rate for CP conjugate process:

$$\left| a_1^* \cdots a_m^* |\mathcal{A}_a| \mathrm{e}^{\mathrm{i}\varphi_a} + b_1^* \cdots b_n^* |\mathcal{A}_b| \mathrm{e}^{\mathrm{i}\varphi_b} \right|^2 \underset{\times\text{-term}}{\supset} (a_1^* \cdots a_m^* b_1 \cdots b_m \mathrm{e}^{\mathrm{i}(\varphi_a - \varphi_b)} + \text{c.c.}) |\mathcal{A}_a \mathcal{A}_b|$$

Difference: $(a_1 \cdots a_m b_1^* \cdots b_m^* - a_1^* \cdots a_m^* b_1 \cdots b_m)(\mathrm{e}^{\mathrm{i}(\varphi_a - \varphi_b)} - \mathrm{e}^{-\mathrm{i}(\varphi_a - \varphi_b)}) |\mathcal{A}_a \mathcal{A}_b|$

$$= 4 \mathrm{Im}[\mathrm{e}^{\mathrm{i}(\varphi_a - \varphi_b)}] \mathrm{Im}[a_1^* \cdots a_m^* b_1 \cdots b_n] |\mathcal{A}_a \mathcal{A}_b|$$

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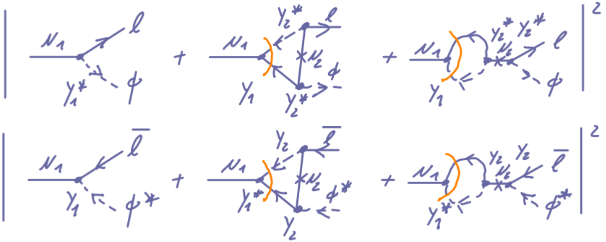
$\mathrm{Im}[\mathrm{e}^{\mathrm{i}\varphi_{a,b}}]$ from coherent superposition of quantum states. For calculable problems, these often correspond

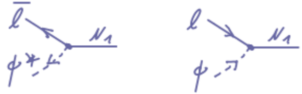
- to on-shell cuts in a Feynman diagram (typical view on "standard" leptogenesis with ultraheavy RHNs)
- or to flavour mixing and oscillations (typical view on leptogenesis with GeV-scale RHNs).

$$\mathcal{L}_{\rm SM} \to \mathcal{L}_{\rm SM} + \tfrac{1}{2}\bar{N}_i^c (i\partial\!\!\!/ - M_{ij}) N_j - Y_{ia}^* \bar{\ell}_a \phi^\dagger N_i - Y_{ia} \bar{N}_i \phi \ell_a;\; a = e, \mu, \tau;\; i = 1, 2, \ldots$$

CP-violating decays/inverse decays



Washout essential to generate net asymmetry from decays/inverse decays



Sphalerons turn lepton into baryon asymmetry

"Wave function" & "vertex" contributions:

$$\varepsilon_{Ni}^{\rm wf} = \frac{1}{8\pi} \sum_{j\neq i} \frac{M_i M_j}{M_i^2 - M_j^2} \frac{\mathrm{Im}[(YY^\dagger)_{ij}^2]}{(Y^\dagger Y)_{ii}}$$

(decay asymmetry: $\varepsilon = \dfrac{\Gamma_{Ni\to\ell H} - \Gamma_{Ni\to\bar{\ell}H^*}}{\Gamma_{Ni\to\ell H} + \Gamma_{Ni\to\bar{\ell}H^*}}$)

$$\varepsilon_{Ni}^{\rm vertex} = \frac{1}{8\pi} \sum_{j\neq i} \frac{M_j}{M_i} \left[1 - \left(1 + \frac{M_j^2}{M_i^2}\right) \log\left(1 + \frac{M_i^2}{M_j^2}\right)\right] \frac{\mathrm{Im}[(YY^\dagger)_{ij}^2]}{(Y^\dagger Y)_{ii}}$$

[Fukugita, Yanagida (1986); Covi, Roulet, Vissani (1996)]

Calculate the asymmetry

Simplest meaningful network of fluid equations describing leptogenesis

$$\frac{\mathrm{d}n_{Ni}}{\mathrm{d}t} + 3Hn_{Ni} = -\Gamma_i(n_{Ni} - n_{Ni}^{\mathrm{eq}}) \qquad \Gamma_i = \frac{|Y_i|^2}{8\pi} M_i$$

$$\frac{\mathrm{d}n_L}{\mathrm{d}t} + 3Hn_L = \varepsilon\Gamma_i(n_{Ni} - n_{Ni}^{\mathrm{eq}}) - Wn_L \qquad W = \frac{\Gamma_i}{4}\left(\frac{M}{T}\right)^{\frac{3}{2}} \mathrm{e}^{-\frac{M}{T}}$$

n_{Ni}: number density of N_i; n_L: lepton charge density; W: washout rate;
$\varepsilon = (\Gamma_{Ni\to\ell H} - \Gamma_{Ni\to\bar{\ell}H^*})/(\Gamma_{Ni\to\ell H} + \Gamma_{Ni\to\bar{\ell}H^*})$: decay asymmetry; T: temperature

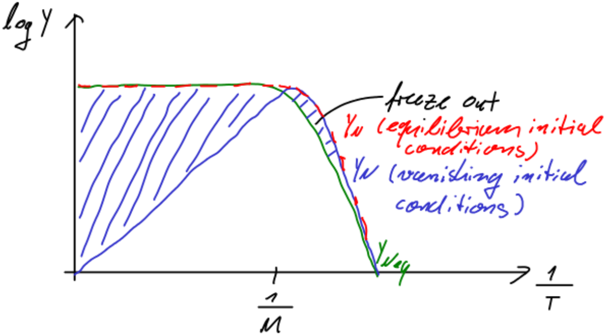
$\longrightarrow$Best compromise between large L violating rate (1st S. condition) and and large deviation from equilibrium (3rd S. condition):
$\Gamma\sim H$ for $T\sim M$ (i.e. at freezeout, when the RHNs become Maxwell suppressed).

$$\longrightarrow\ Y^2 M/(8\pi) \sim T^2/m_{\mathrm{Pl}} \sim M^2/m_{\mathrm{Pl}} \overset{m\sim\frac{Y^2v^2}{M}}{\Rightarrow} m \sim 8\pi v^2/m_{\mathrm{Pl}} \sim 0.1\,\mathrm{meV}$$

Light neutrino nass scale points to role of RHNs in baryogenesis

- Out-of-equilibrium property of the N independent of the mass scale M
- Tendency of being somewhat close to equilibrium, *i.e.* $\Gamma \gg H$ around $T\sim M$ $\to$ strong washout
  However, $\exists$ a lot of parametric freedom

Consider $Y_N = \frac{n_N}{s}$, production, decay via Yuakwa couplings



Lepton asymmetry settles as a balance between production & washout during freeze-out

Strong washout removes dependence on intial conditions

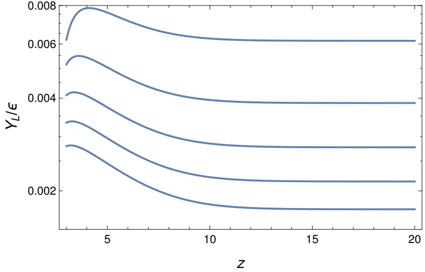
RHNs nonrelativistic during freeze-out $\rightarrow$ Details of momentum distribution are irrelevant, thermal effects negligible at leading order

Solutions for the freeze-out asymmetry

Varying washout strength

```
YNeq[z_] = 2^(-1/2) * Pi^(-3/2) * z^(3/2) * Exp[-z]; ϵ = 1;
S = Table[NDSolve[
    {YL'[z] == ϵ * D[YNeq[z], z] - Kws / 4 * z^(5/2) * Exp[-z] * YL[z], YL[0.1] == 0},
    YL, {z, 0.5, 100}], {Kws, {10, 15, 20, 25, 30}}];
```

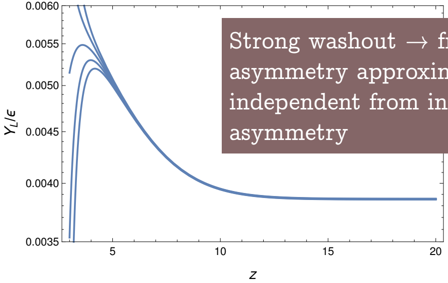
Out[4]=



Varying initial conditions

```
YNeq[z_] = 2^(-1/2) * Pi^(-3/2) * z^(3/2) * Exp[-z]; ϵ = 1;
With[{Kws = 15},
  S = Table[NDSolve[
       {YL'[z] == ϵ * D[YNeq[z], z] - Kws / 4 * z^(5/2) * Exp[-z] * YL[z], YL[0.1] == IC},
       YL, {z, 0.5, 100}], {IC, {-1, -0.5, 0, 0.5, 1}}];
];
```

Out[7]=



Strong washout $\rightarrow$ freeze-out asymmetry approximately independent from initial asymmetry

Analytic approximation:

$\eta_B \simeq 0.96 \times 10^{-2} \varepsilon \kappa$, where [Buchmüller, Di Bari, Plümacher (2004)]

$K = \frac{\Gamma_1}{H}\Big|_{T=M_1}$ washout strength, $\kappa = \frac{2}{z_B(K) K}$ efficiency factor, $z_B(K) = 1 + \frac{1}{2}\log\left(1 + \frac{\pi K^2}{1024}\left[\log\frac{3125\pi K^2}{1024}\right]^5\right)$

More numerology

Unless there is resonant enhancement, leptogenesis in the strong washout regime requires $M \gtrsim 10^9$ GeV because $\varepsilon \sim Y^2$ [Davidson, Ibarra (2002)].

Naturalness: In absence of SUSY or other cancellation mechanism, the RHNs will contribute to the Higgs mass. In order to avoid destabilization, require

$$\Delta m_\phi^2 = \sum_i \frac{[Y^\dagger Y]_{ii}}{4\pi^2} M_i^2 \log \frac{M_i}{\mu} \sim \frac{mM^3}{4\pi^2 v^2} \log \frac{M}{\mu} \lesssim m_\phi^2 \to M_N \lesssim 3 \times 10^7 \,\text{GeV}$$

[Vissani (1997)]

Simple scenario, conceptually & calculationally

Millielectronvolt neutrino masses point to sweet spot: mildly strong washout regime
$\longrightarrow$ Independence of initial conditions, yet large efficiency

Strong washout observation independent of M, mild tension between naturalness bound and enough CP voilation (in absence of workarounds...)

Simple (in terms of vacuum $1 \leftrightarrow 2$ rates), robust prediction because of nonrelativistic RHNs

Contents

Leptogenesis

Why going beyond the simplest variant

Even in type-I seesaw framework, several motivations:

- Real intermediate state problem
- Flavoured leptogenesis
- Standard Model spectator processes
- Resonant leptogenesis
- GeV-scale RHNs/ARS
- Additional source from mixing of lepton doublets [BG (2012)]

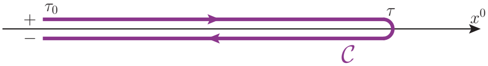
$|\mathrm{in}\rangle$: state of the system at time $t = 0$

Wightman function: $\mathrm{i}\Delta^{-+} = \langle \mathrm{in}|\phi^*(\vec{x}, t)\phi(\vec{x}', t')|\mathrm{in}\rangle$
$\longrightarrow$ e.g. energy density, four-current: $j^\mu(x) = -\mathrm{i}\lim_{x'\to x}(\partial_x^\mu - \partial_{x'}^\mu)\mathrm{i}\Delta^{-+}(x, x')$

Note: "in-in" correlators instead of "in-out" used in scattering theory $S_{fi} = {}_f\langle \mathrm{out}|\,U(t, t')|\mathrm{in}\rangle_i$

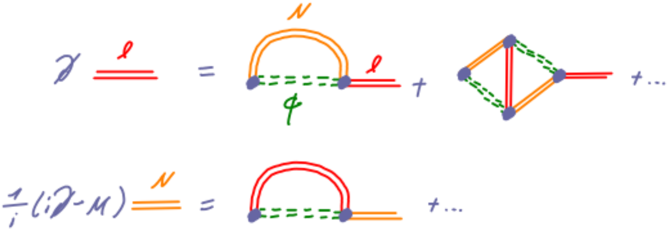
$+/-$ indices denote boundary conditions, e.g. $-+$ without ordering, $++$ time-ordered,...

$\longrightarrow$ Path integral on closed time path (CTP):



$\longrightarrow$

Real-time evolution through Schwinger–Dyson equations for CTP correlation functions



- Want: A set of equations describing a non-equilibrium system of a large number of particles
- Should be derivable from first principles
  - classical: Liouville equations (with interaction potentials)
  - quantum: Schwinger-Dyson equations in Closed-Time-Path (CTP) formalism
- Truncations/approximations
  → Reduction to irreversible kinetic equations in the form of Boltzmann equations (or variants thereof taking e.g. account of flavour coherence, quantum statistics)
  → Further reduction down to fluid equations (in terms of number densities and bulk flows instead of particle distributions)
  → Allows for analytical/numerical treatment

Liouville/Schwinger-Dyson equations (microscopic kinetic equations)

↓

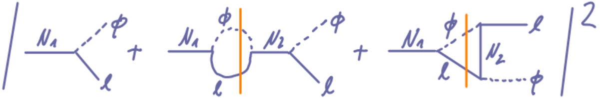
Boltzmann-like kinetic equation for distribution functions

↓

fluid equations for number densities/ bulk flows

Real intermediate state (RIS) problem

- Interference of tree & loop amplitudes $\rightarrow$ CP violation.



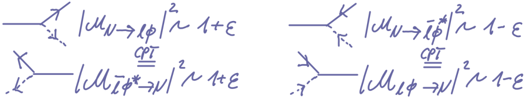
$(*)$

- CP violating contributions (CP-even phase) from discontinuities $\rightarrow$ loop momenta where cut particles are on shell
- Is  an extra process or is it already accounted for by

 and  ?

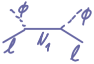
- Including $(*)$ only $\rightarrow$ CP asymmetry is already generated in equilibrium. ↯ CPT ↯ theorem.
  (CPT invariance requires to break T thermodynamically in order to make CP effective)

Consider the squared matrix elements, ε being the decay asymmetry



Naive multiplication suggests that an asymmetry is generated already in equilibrium:

$\Gamma_{\bar{\ell}\phi^*\to\ell\phi} \sim 1+2\varepsilon$, $\Gamma_{\ell\phi\to\bar{\ell}\phi^*} \sim 1-2\varepsilon$

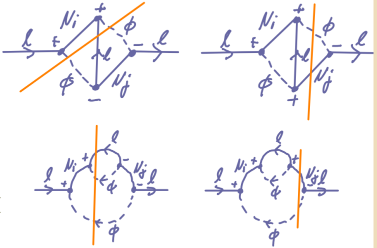
Ad hoc fix: Impose CPT, subtract real intermediate states (RIS) from 

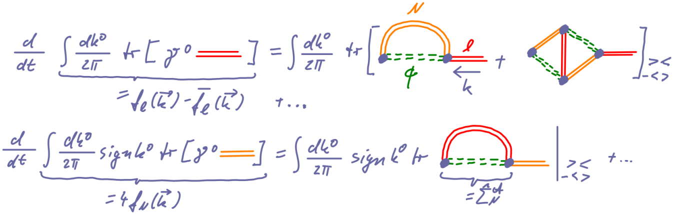
[Kolb, Wolfram (1980)]

CTP approach readily yields <u>inclusive</u> rates for the creation of the charge asymmetry

No need to separately remove unwanted/unphysical contribution <u>a posteriori</u>

[Garny, Hohenegger, Kartavtsev, Lindner (2009); Beneke, BG, Herranen, Schwaller (2010)]





Evolution of matrix-valued RHN distributions δf_{Nh} (i.e. deviation from equilibrium f_N^{eq})

$$\delta f'_{Nh} + \frac{a^2(\eta)}{2k^0}\mathrm{i}[M^2, \delta f_{Nh}] + f_N^{\mathrm{eq}\prime} = -2\left\{\mathrm{Re}[Y^* Y^t]\frac{k\cdot\hat{\Sigma}_N^{\mathcal{A}}}{k^0} - \mathrm{i}h\mathrm{Im}[Y^* Y^t]\frac{\tilde{k}\cdot\hat{\Sigma}_N^{\mathcal{A}}}{k^0}, \delta f_{Nh}\right\}$$

$\hat{\Sigma}_N^{\mathcal{A}}$: spectral (cut part) self energy, $a(\eta), \eta$: scale factor and conformal time, $\prime \equiv \mathrm{d}/\mathrm{d}\eta$, h: helicity, $\tilde{k} = (|\mathbf{k}|, |k^0|\mathbf{k}/|\mathbf{k}|)$

- $\mathrm{i}[M^2, \delta f_{Nh}]_{ij} = \mathrm{i}(M_i^2 - M_j^2)\delta f_{Nhij}$ for diag. $M^2 \to$ RHN "flavour" oscillations
- Off-diagonal entries of $\delta f_{Nh\,ij}$ correspond to interferences and give rise to CP-even phases
- If $\delta f'_{Nh}$ can be neglected, recover result from "standard resonant leptogenesis" → next slide
- Evolution equations well-behaved for $\Delta M^2 \to 0$; solutions δf_{Nh} enter into resummed RHN propagators

[BG, Herranen (2010); Iso, Shimada (2014); BG, Gautier, Klaric (2014)]

Wave-function contribution:

$$\varepsilon_{Ni}^{\mathrm{wf}} = \frac{1}{8\pi} \sum_{j\neq i} \frac{M_i M_j (M_i^2 + M_j^2)}{(M_i^2 - M_j^2)^2 + R} \frac{\mathrm{Im}[(YY^\dagger)_{ij}^2]}{(Y^\dagger Y)_{ii}}$$

In the degenerate limit, this will dominate over the vertex contribution.

Proposed forms for regulator R ($\bar{M} = (M_i + M_j)/2$):

- $R = \frac{\bar{M}^4}{64\pi^2} (YY^\dagger)_{jj}^2 = \bar{M}^2 \Gamma_j^2$ [Pilaftsis (1997); Pilaftsis, Underwood (2003)]
- $R = \frac{\bar{M}^4}{64\pi^2} \left([YY^\dagger]_{ii} - [YY^\dagger]_{jj} \right)^2$ [Anisimov, Broncano, Plümacher (2005)]
- $R = \frac{\bar{M}^4}{64\pi^2} \left([YY^\dagger]_{ii} + [YY^\dagger]_{jj} \right)^2$ [Garny, Hohenegger, Kartavtsev (2011)]
- $$R = \frac{\bar{M}^4}{64\pi^2} \frac{([YY^\dagger]_{11} + [YY^\dagger]_{22})^2}{[YY^\dagger]_{11}[YY^\dagger]_{22}} \left((\mathrm{Im}[YY^\dagger]_{12})^2 + \det YY^\dagger \right)$$
  Obtained by algebraic solution to oscillation equation, neglecting $\delta f_N'$
  [BG, Gautier, Klaric (2014); Iso, Shimada (2014)]

Resonant Leptogenesis in the Strong Washout Regime

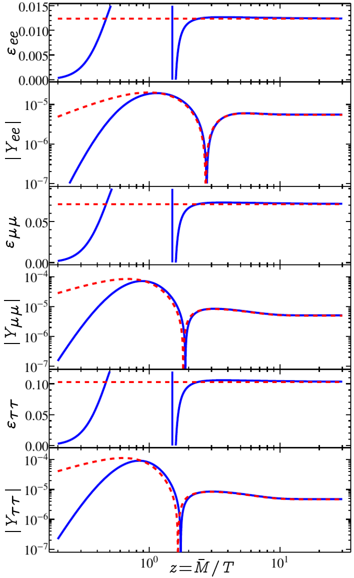
Quasistatic Approximation

- Neglect derivative term provided the eigenvalues (that originate from the mass and the damping terms) in the kinetic equation for are larger than the Hubble rate H $\to$ Obtain linear system of equations for δf_{Nh}.
  [BG, Gautier, Klaric (2014); Iso, Shimada (2014)].
- Regulator:

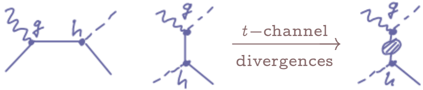
$$R = \frac{\bar{M}^4}{64\pi^2} \frac{([YY^\dagger]_{11}+[YY^\dagger]_{22})^2}{[YY^\dagger]_{11}[YY^\dagger]_{22}} \times \left((\mathrm{Im}[YY^\dagger]_{12})^2 + \det YY^\dagger\right)$$

- Applies in strong washout regime, *i.e.* a large portion of parameter space.

blue: full result; red: result using effective decay asymmetry ε; $Y_{aa} = n_{Laa}/s$. Here, $\bar{M}\Gamma \gg \Delta M^2$.



SM Yuakwa-mediated processes at finite temperature:

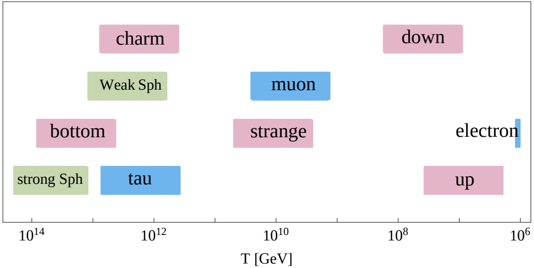


$\Gamma_X \sim T g^2 h^2 \log g$

Cf. Hubble rate $H \sim T^2$

$\rightarrow$ As the Universe cools, more and more SM processes come into equilibrium.

Besides Yukawa mediated processes, there are also the chiral anomalies (strong and weak sphalerons).



Temperature bands $T_X \leq T \leq 20 T_X$ where T_X is the equilibration temperature $\Gamma_X(T_X) = H(T_X)$.

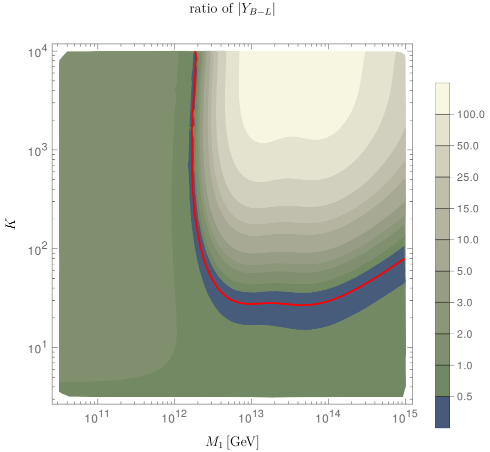
Asymmetries are transferred partly to all SM degrees of freedom $\rightarrow$ suppression of washout.
[Barbieri, Creminelli, Strumia, Tetradis (2000)]

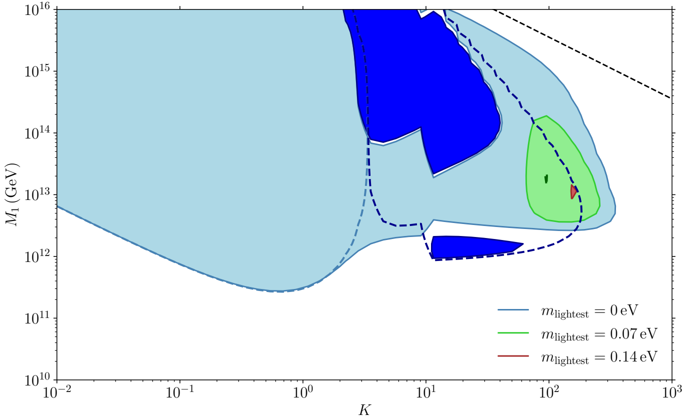
RHNs may equilibrate at $T \sim M$ $\longrightarrow$ cannot use relativistic/nonrelativistic approximations $\longrightarrow$ KLN-type cancellation of real/virtual IR divergences at finite T [BG, Glown, Herranen (2013); Ghilgieri, Laine (2016)]

Vanishing initial conditions

[BG, Klose, Tamarit (2019)]

- Deviation from equilibrium is large for $T \gg M_1$
- Asymmetry produced at that time is hidden in spectators (here: b-quarks), partially protected from washout
- Requires the calculation of unflavoured asymmetries from RHN production in relativistic regime
- Equilibrium intitial conditions: $\mathcal{O}(1)$ effect compared to fully equilibrated spectator approximation [BG, Schwaller (2014)]





[BG, Wang (2024)]

Regions in K–M-plane where leptogenesis is viable (normal mass hierarchy, vanishing initial RHN abundance)

cf. [Buchmüller, DiBari, Plümacher (2003)]

Solid: full analysis

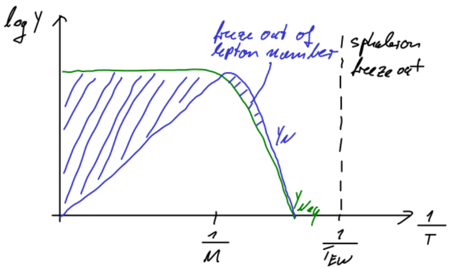
Dashed: assume fully equilibrated spectators

Shading of blue: sign flip

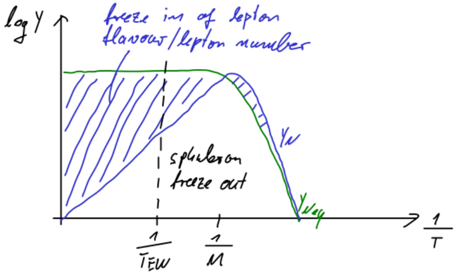
With $M_N \ll T_{\rm EW} \sim 150$GeV lepton number violation frezzes out only after the electroweak crossover

Also for $T \gg T_{\rm EW}$, lepton number violation suppressed, however not flavour violation

Produce flavour asymmetries early through freeze in, convert these partly to net lepton asymmetry before $T_{\rm EW}$ [Akhmdov, Rubakov, Smirnov (1998); Shaposhinkov, Asaka (2005)]



Standard leptogenesis



ARS-type leptogenesis with GeV-scale RHNs

Enhanced asymmetries

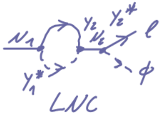
Standard leptogenesis

LNV Majorana mass insertions necesseary

$\rightarrow \varepsilon \propto \frac{M_1 M_2}{M_1^2 - M_2^2}$

ARS-type leptogenesis

No LNV Majorana mass insertions

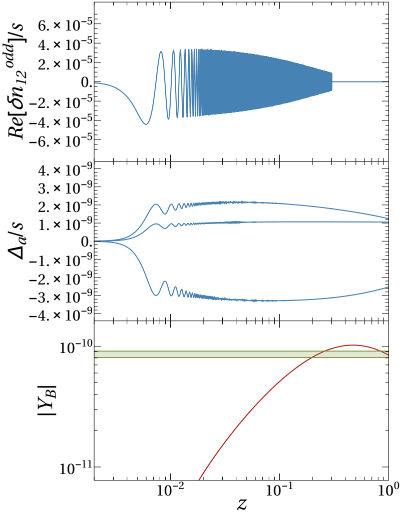


Gauge interactions at finite T enhance phase space

$\rightarrow \varepsilon \propto \frac{T^2}{M_1^2 - M_2^2}$

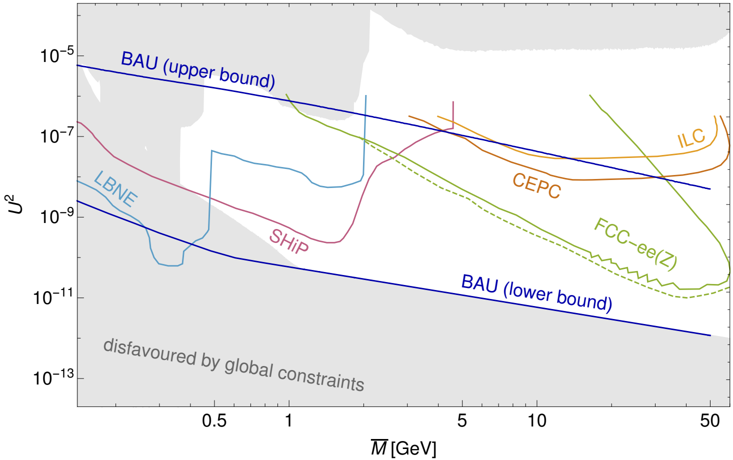
Off diagonal correlations build up through flavour oscillations among the RHNs. These first occur at the temperature $T_{\rm osc} \sim (|M_i^2 - M_j^2| m_{\rm Pl})^{1/3}$,
i.e. for $M_{1,2} \sim$ GeV $\rightarrow$ $T_{\rm osc} \sim 10^5$GeV
$\rightarrow$ Large enhancement of asymmetry opens up possibility of leptogenesis from GeV-scale RHNs without strong parametric tuning [Drewes, BG (2012)], no/alleviated conflict with Davidson–Ibarra bound and stability of electroweak scale

NB for $M_{1,2} \gg T_{\rm EW}$, these early asymmetries typically experience strong washout.
For exceptions, see [BG (2014)]



- $T\Gamma \ll \Delta M^2 \rightarrow$ oscillatory regime
- RHNs perform first oscillation at $T_{\rm osc} \sim (|M_i^2 - M_j^2| m_{\rm Pl})^{1/3}$
- Off-diagonal correlations lead to CP violating source for lepton flavour asymmetries (purely flavoured)
- Contributions from subsequent oscillations average out
- Transfer of asymmetries into helicity asymmetries of RHNs leads to $Y_L \neq 0$.
- Asymmetry frozen in at $T_{\rm EW}$, where sphalerons are quenched by the developing Higgs vev
- $\delta n = \int d^3k/(2\pi)^3 \delta f_N \rightarrow$ momentum averaging

$z = T_{\rm EW}/T$; Δ_a: lepton asymmetry in flavour $a = e, \mu, \tau$; δn: number density of RHNs; Y_B: entropy-normalized baryon asymmetry; s: entropy density. [Drewes, BG, Gueter, Klarić (2016)]



[Drewes, BG, Gueter, Klarić (2016)]

Contents

Leptogenesis

Conclusions

Leptogenesis an economic explanation for the matter–antimatter asymmetry

Basic variant is a simple paradigm for baryogenesis from out-of-equilbrium decays

In the seesaw model parameter space, deviations from the simplest variant are the rule, not an exception.
$\longrightarrow$ Develop and test nonequilbrium methods, spinoffs for more involved settings such as electroweak baryogenesis

ARS/GeV–scale scenario plausible with possible long-term testability

Flavoured leptogenesis

- Neutrino Yukawa couplings: $Y_{ia}\bar{N}_i\ell_a\phi$
- When insensitive to lepton flavour, can $\ell_a \to U_{ab}\ell_b$, $Y_{ia} \to Y_{ib}U^\dagger_{ba}$ such that

$$Y = \begin{pmatrix} Y_{11} & 0 & 0 \\ Y_{21} & Y_{22} & 0 \\ Y_{31} & Y_{32} & Y_{33} \end{pmatrix}$$

$\longrightarrow$ N_1 decays only produce $(U\ell)_1$, which is a linear combination of ℓ_e, ℓ_μ, ℓ_τ.

$\longrightarrow$ Back to flavour basis – quantum correlations of charge densities:

$$\begin{pmatrix} q_{ee} & q_{e\mu} & q_{e\tau} \\ q_{\mu e} & q_{\mu\mu} & q_{\mu\tau} \\ q_{\tau e} & q_{\tau\mu} & q_{\tau\tau} \end{pmatrix}$$

- When $H \sim \frac{T^2}{m_{\rm Pl}} \lesssim \Gamma_{\tau,\mu} \sim h^2_{\tau,\mu}T$, *i.e.* $T \lesssim 10^{12}\mathrm{GeV}$ (for τ) or $T \lesssim 10^9\mathrm{GeV}$ (for μ), the flavour coherence is destroyed by the SM lepton Yukawa couplings $h_{\tau,\mu}$.

$$\rightarrow \begin{pmatrix} q_{ee} & 0 & 0 \\ 0 & q_{\mu\mu} & 0 \\ 0 & 0 & q_{\tau\tau} \end{pmatrix}$$

$\longrightarrow$ The resulting linear combination is only partly aligned with the one that is produced in the decays of N_1. $\longrightarrow$ $\mathcal{O}(1)$ suppression of washout. [Abada, Davidson, Josse-Michaux, Losada, Riotto (2006); Nardi, Nir, Roulet, Racker (2006)]

- For initially lepton flavour violating contributions with vanishing $L = L_e + L_\mu + L_\tau$: washout of different flavours $\to$ lepton number violating asymmetry at freeze out that receives contribution from the PMNS phase δ – but from other phases as well. [Pascoli, Petcov, Riotto (2006)]
- Even for $T \gtrsim 10^{12}\mathrm{GeV}$, the asymmetries from the decays of the heavier RHNs correspond to linear combinations of flavour that are in general misaligned with the one washed out by the lightest of the RHNs [Di Bari (2005)]. $\to$ Richer phenomenology, less predictivity.

- Kinetic eqs. for number densities & flavour correlations of (anti-)leptons $\delta n_\ell^\pm$:

$$\frac{\partial \delta n^\pm_{\ell ab}}{\partial t} = \underbrace{\pm S_{ab}}_{\substack{CP\text{-}\\ \text{violating}\\ \text{source}}} \underbrace{\mp \mathrm{i}\Delta\omega^{\rm th}_{ab}\delta n^\pm_{\ell ab}}_{\substack{\text{oscillations}\\ \text{induced by}\\ \text{thermal masses}}} - \underbrace{[W, \delta n^\pm_\ell]_{ab}}_{\text{washout}} - \underbrace{\gamma^{\rm bl}\left(\delta n^+_{\ell ab} + \delta n^-_{\ell ab}\right)}_{\substack{\text{flavour-blind}\\ \text{pair-creation \&}\\ \text{annihiliation}}} \underbrace{-\Gamma^{\rm fl}_{ab}}_{\substack{\text{flavour-}\\ \text{sensitive}\\ \text{damping}}}$$

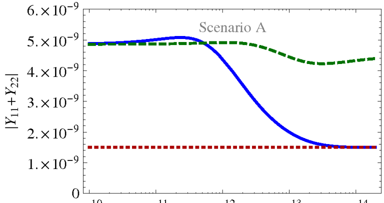
$$\Gamma^{\rm fl} \propto h_\tau^2 \left[\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \delta n^\pm_\ell \right] - 2h_\tau^2 \delta n^\pm_{\rm R} \to \text{directly damps off-diagonal correlations}$$

- thermal masses like to induce flavour oscillations in opposite directions $\delta n^+_{\ell ab}$ $\delta n^-_{\ell ab}$
  oscillations overdamped
  $W^{0,\pm}, B$ like to keep these aligned

$$\Gamma^{\rm direct} \sim (h_{aa}^2 + h_{bb}^2)\, T$$

$$\Gamma^{\rm overdamped} \sim \frac{(h_{aa}^2 - h_{bb}^2)^2}{g_2^4}\, T$$

where $a, b = e, \mu, \tau$



- Can interpolate between fully flavoured and unflavoured regimes.

[Beneke, BG, Herranen, Fidler, Schwaller (2010)]