
Of Cookbooks and Fairy Tales:
How neutrinos could make
the Universe we see
Sacha Davidson, IPN de Lyon, France

Neutrinos and the Matter of the Universe: Outline

1. the Universe contains more matter than anti-matter (data).
   This excess should be *generated* during life of Universe ($\Rightarrow$ required ingredients...).

2. We and this room are traversed by *hoards* of hardly-interacting neutrinos. These have small masses (data). A simple model to explain this is the seesaw: little neutrinos have BIG brothers with **BIG** masses.

3. The "leptogenesis" fairy tale: the big brothers generated the matter excess during the first "yoctosecond".

4. quelques précisions — why washout matters
   — where does one get Boltzman Equations from?

With thanks to C Perrault and A Strumia and to my "leptogenesis" collaborators: A Abada, L Boubekeur, B Campbell, J Ellis, J Garayoa, A Ibarra, F-X Josse-Michaux, K Kimmolainen, R Kitano, M Losada, E Nardi, Y Nir, K Olive, F Palorini, M Peloso, A Riotto, N Rius and L Sorbo

The Excess of Matter over Antimatter in the Universe

we see $\left.\begin{array}{l}\text{the earth}\\ \text{the solar system}\\ \text{the galaxy}\\ \text{galaxy clusters}\end{array}\right\}$ are made of matter (no γ rays from annihilation)

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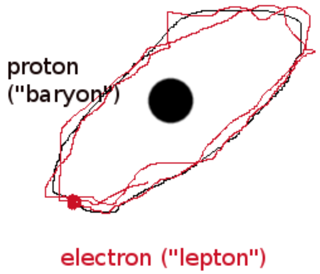
In the lab, B and L are conserved.

Different baryons (n, p) can turn into each other...

Different leptons (ν, e) can turn into each other...



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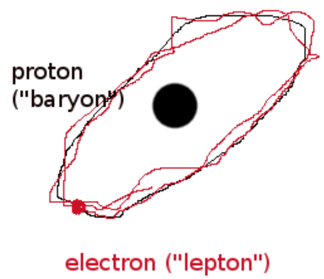

Matter excess = baryon excess, so this implies a baryon asymmetry :

$$7\frac{n_B - n_{\bar{B}}}{s} \simeq \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \left\{\begin{array}{ll}\sim \text{few} \times 10^{-11} & \text{luminous}\\ 2-6 \times 10^{-10} & BBN\\ 6 \times 10^{-10} & WMAP\end{array}\right.$$

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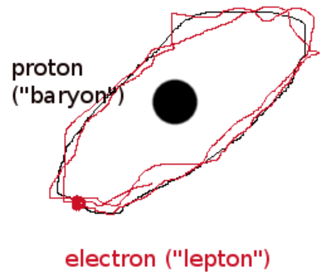

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not worry about lepton asymmetry, because there is a cosmic background of ... *NEUTRINOS!*

A Tangent

...

Neutrinos

Three neutrinos of the Standard Model ($\nu_e,\ \nu_\mu,\ \nu_\tau$)

(almost) non-interacting:

- subject to gravity (impact in cosmology)
- “weak” interactions: nuclear decay $n \longrightarrow p^+ + e^-\bar{\nu}$ needs $\bar{\nu}$ for momentum conservation
  ex: sun = fusion reactor:
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are they massless?

exactly massless in the “Standard Model”
But some puzzling ν data, 60’s to today ...

1. solar neutrino problem
   measured flux $\sim 1/3 - 1/2$ of expected from solar luminosity
2. atmospheric neutrino problem
   wrong ν_μ to ν_e ratios from cosmic rays...

$\Leftrightarrow$ ν **fluxes not match expectations**
$\Rightarrow$ explained by small $m_\nu \sim 10^{-7} - 10^{-9} m_e$ **BSM!**
confirmed by beam expts

Minkowski, Yanagida
Mann Ramond Slansky

The Seesaw

data: $0 < m_\nu \ll m_e$. The "seesaw" is a model to obtain this...

- The mass matrix in one generation(m_D is the pivot):

$$(\nu \; N) \begin{bmatrix} 0 & m_D \\ m_D & M \end{bmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix} \qquad\qquad m_D \ll M$$

approx eigenvals : $m_\nu \simeq m_D^2/M$ for ν , M for N

NB: no complex conjugate on any fields! If ν is a lepton, N and anti-lepton, M violates lepton number

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• The Lagrangian: one gen of Standard Model leptons, + N

(allows "Dirac" masses for νs , ϕ is Higgs, N has no Standard Model gauge intereactions = so can have a large mass)

$$\mathcal{L}_{lep}^{Yuk} = h_e(\overline{\nu_L}, \overline{e_L}) \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} e_R \;-\; \lambda(\overline{\nu_L}, \overline{e_L}) \begin{pmatrix} -\phi^{0*} \\ \phi^- \end{pmatrix} N^c \;+\; M\overline{N}N^c$$

$$m_e\overline{e_L}e_R \qquad\qquad + m_D\overline{\nu_L}N^c \qquad\qquad + M\overline{N}N^c$$

If ν is a lepton, N an anti-lepton, M violates lepton number by two units..

• One last thing: *three* generations of leptons in the Standard Model

λ, M are 3×3 matrices $\Rightarrow 6 \times 6$ mass matrix...unremoveable phases!

phases make particles and antiparticles behave differently $\equiv$ "CP violation"!

Back to

the Matter Excess of the Universe

Recall: the U we see is made of matter ($\Rightarrow$ "baryons"), not anti-matter. Measured excess

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Back to the matter excess — where did it come from?

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   X no! After birth of U, there was "inflation"
   - inflation $\equiv V_U \longrightarrow> 10^{90} V_U$
   - only theory explaining coherent temperature fluctuations in microwave background that arrive from causally disconnected regions...

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   - inflation $\equiv V_U \rightarrow > 10^{180} V_U$
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3. created/generated/cooked during life of the Universe...

The Big Cookbook
for the
Baryon Asymmetry of the Universe

Making a Matter Excess : three required ingredients

1. B violation : if Universe starts in state of $n_B - n_{\bar{B}} = 0$, need $\not{B}$ to evolve to $n_B - n_{\bar{B}} \neq 0$

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(thanks to V Rubakov)

B+L violation in the Standard Model

In field theory of massless chiral fermions:

$$\partial_\mu J_5^\mu = \overline{\psi_R}\gamma^\mu\partial_\mu\psi_R - \overline{\psi_L}\gamma^\mu\partial_\mu\psi_L = \begin{cases} 0 & \text{classical theory (no loops)} \\ \propto F\tilde{F} & \text{when renormalise} \\ & \text{"winding number"}, F = [D_\mu, D_\nu] \end{cases}$$

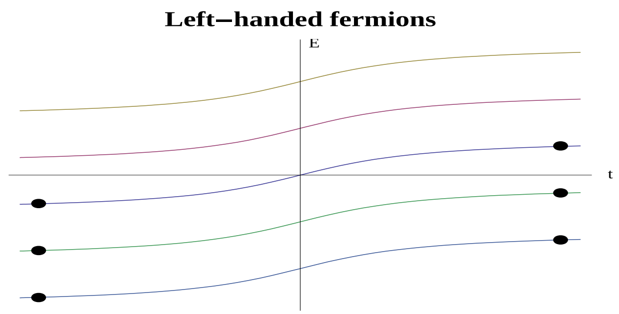
For LH SU(2) doublet ψ_L^i of the SM:

$$\partial^\mu(\overline{\psi_L^i}\gamma_\mu\psi_L^i) = \frac{1}{64\pi^2}W_{\mu\nu}^A\widetilde{W}^{\mu\nu A}.$$

If define $Q^i(t) = \int \overline{\psi_L^i}\gamma_0\psi_L^i d^3x$, $\Delta Q^{\,i} = Q^{\,i}(+\infty) - Q^{\,i}(-\infty)$:

$$\Delta Q^{\,i} = \frac{1}{64\pi^2}\int d^4x W_{\mu\nu}^A\widetilde{W}^{\mu\nu A}$$

then gauge field configuration of non-zero winding number acts as source of fermions



$t \longrightarrow$

't Hooft
Kuzmin Rubakov+
Shaposhnikov

SM B+L violation : rates

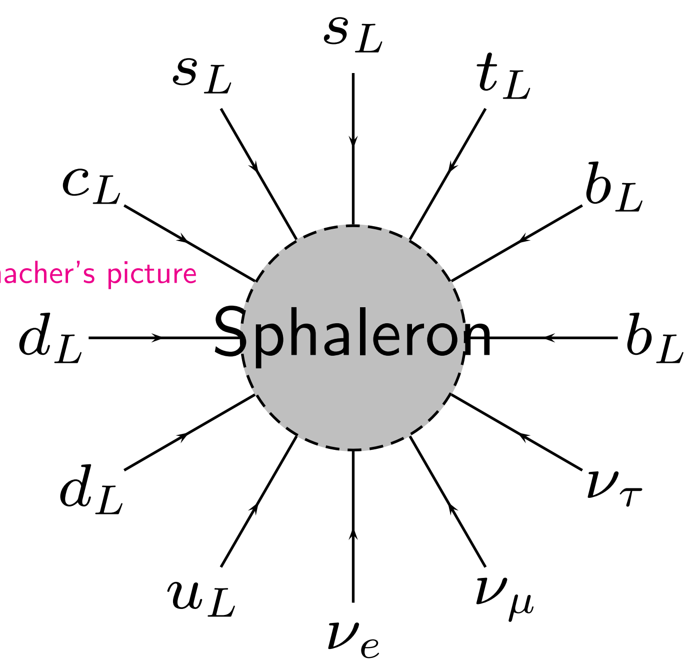
Baryon number — is experimentally conserved
is conserved in the renormalisable SM Lagrangian

But: there are SU(2) gauge field configurations of non-zero winding number that produce one of every fermion doublet. How fast are they?

A tunneling process ("instanton") at $T = 0$, $\Gamma \propto e^{-8\pi/g^2}$ (?).

At $0 < T < T_{EPT}$, can climb over the barrier : $\Gamma_{\not{B+L}} \sim \begin{array}{ll} e^{-m_W/T} & T < EWPT \\ \alpha^5 T & T > EWPT \end{array}$

Plumacher's picture



$\Rightarrow$ fast SM $\not B$ at $T > EPT$

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All ingredients present in Standard Model of part phys and of cosmo !!
— not combine to make enough matter
+ *need particles from Beyond the Standard Model? Like N?*

The Big Cookbook for the Baryon Asymmetry of the Universe

Leptogenesis

reflections after consulting the index of the cookbook

- one measured number: the baryon to photon ratio

$$Y_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6 \pm 1) \times 10^{-10} \ \ (CMB)$$

- required ingredients ($\not{B}$, $\not{CP}$, $\not{TE}$) are present in the SM (of part phys and cosmo)...but...its not just mix and stir: they $don't$ combine to make a baryon asymmetry.
- $\Rightarrow$ we need Beyond the Standard Model (BSM) physics ! ...but...
  BSM models have $many$ parameters...

reflections, caveats

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criteria to select a recipe :
- BSM physics that is otherwise motivated (the seesaw generates neutrino masses)
- can generate the baryon asymmetry without making the proton decay ($e.g.$ "sphalerons")
- as simple (singlet seesaw, with ? hierarchical masses?) and parameter-independent (thermal production) as possible
- it works = asymmetry big enough

$\Rightarrow$ *THERMAL LEPTOGENESIS IN THE SINGLET SEESAW*
with hierarchical singlet masses, and flavour (I am cooking :))

The Fairy Tale of Leptogenesis

The Fairy Tale of flavoured thermal leptogenesis with hierarchical singlet masses

Fukugita Yanagida
Buchmuller et al
Covi et al
Branco et al
Giudice et al
...

A Universe was born.

Fairy Godmothers come to the Christening of the Universe

Gifts from Fairy Godmothers

A fairy gives the Standard Model to the Universe.

Gifts from Fairy Godmothers

A fairy gives the Standard Model to the Universe.
And another Fairy gives the singlet seesaw. *WITH* hierarchical masses for the N_i

The adventure begins...

After inflation, vaccuum energy density is transfered to a hot thermal soup at $T_{reheat} \sim 10^{11\pm2}$ GeV (made of particles with gauge interactions. No N_1s.). Then... Universe expands and cools...

- $\not{TE}$ dynamics: in the thermal soup after inflation, needs the timescale for some N_1 interactions $> \tau_U$ (age of U at that temp).

- $\not{CP}$, $\not{L}_\alpha$: From M_1 and $\lambda_{\alpha 1}$. Generate lepton asymmetry in flavour α.

  λ is neutrino Yukawa, connects $\nu \leftrightarrow N$

- $\not{B+L}$: non-perturbative SM processes (sphalerons): lepton asymmetry $\longrightarrow$ baryon asymmetry

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim \frac{1}{3} \frac{n_\ell - n_{\bar{\ell}}}{n_\gamma}$$

Producing Ns

1. First produce a population of N_1s, via *e.g.* $(q\ell_\alpha \longrightarrow Nt_R)$ (α = lepton flavour/generation).
   Assume $\Gamma_{prod} \gg H_U$ (timescale for production interactions is shorter than the age of the U)
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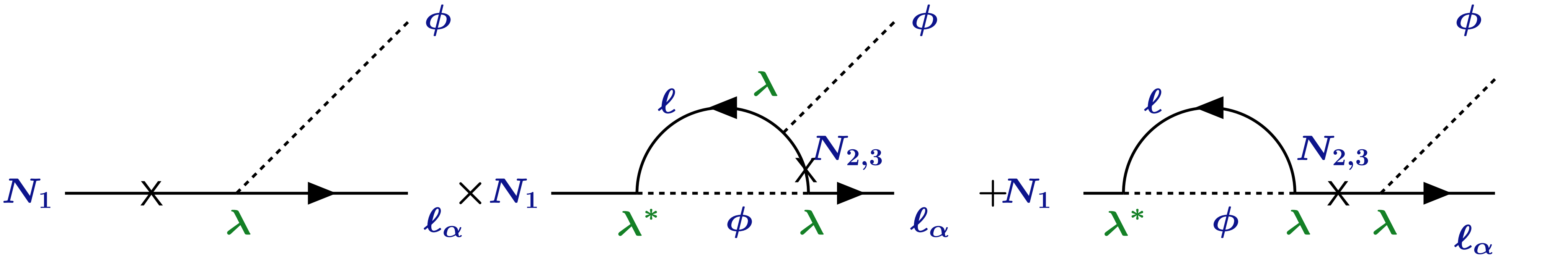
Hamaguchi,Murayama+
Yanagida
Davidson Ibarra

$\not{C}\not{P}$ and $\not{L}$ (for $M_1 \ll M_2, M_3$): why $M_1 \gtrsim 10^9$ GeV

$\not{C}\not{P}$, $\not{L}$: N_1 interactions generate an excess of leptons ℓ_α with respect to anti-leptons $\bar{\ell}_\alpha$. ($\not{C}\not{P}$ from tree $\times$ loop interference):

$$\epsilon^{\alpha\alpha} = \frac{\Gamma(N_1 \to \phi\ell_\alpha) - \Gamma(\bar{N}_1 \to \bar{\phi}\bar{\ell}_\alpha)}{\Gamma(N_1 \to \phi\ell) + \Gamma(\bar{N}_1 \to \bar{\phi}\bar{\ell})} \qquad \text{(recall } N_1 = \bar{N}_1\text{)}$$

$$\sim 10^{-6} \qquad \Rightarrow \sim 1 \text{ excess lepton}/10^6 \; N \text{ decays}$$



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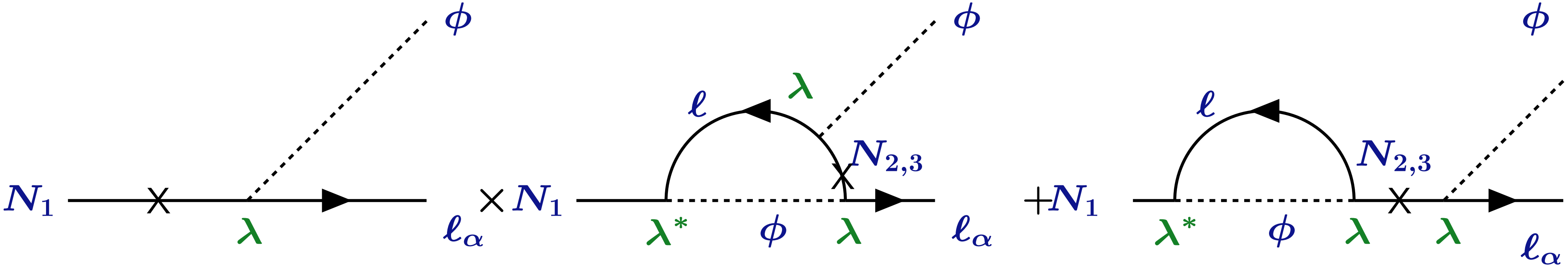

Can show : $\displaystyle\sum_\alpha \epsilon^{\alpha\alpha} < \frac{3}{16\pi}\frac{(m_3 - m_1)M_1}{\langle H_u \rangle^2} \sim 10^{-6}\frac{M_1}{10^9 \text{GeV}} \Rightarrow M_1 \gtrsim 10^9$ GeV

...and enter the wolf: thermal equilibrium

need $\not{T}\not{E}$ dynamics: if the $\not{L}$ interactions of N_1 are in equilibrium, they will destroy any asymmetry in the Standard Model leptons.

How big a lepton asymmetry survives ?

1. First produce a population of N_1s, via *e.g.* $(q\ell_\alpha \to N t_R)$ (α = lepton flavour/generation).
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   Produce a lepton asymmetry in the decays of N_1.
   The lepton asym in flavour α (produced from N_1 decay) can survive *after* Inverse Decays from flavour α turn off ($\Gamma_{ID}(\ell_\alpha\phi \to N) < H_U$)

$$\Gamma_{ID}(\ell_\alpha\phi \to N) \simeq \Gamma(N \to \ell_\alpha\phi)e^{-M_1/T} < H_U$$

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   Produce a lepton asymmetry in the decays of N_1.
   The lepton asym in flavour α (produced from N_1 decay) can survive *after* Inverse Decays from flavour α turn off ($\Gamma_{ID}(\ell_\alpha\phi \rightarrow N) < H_U$ = U expansion)

$$\Gamma_{ID}(\ell_\alpha\phi \rightarrow N) \simeq \Gamma(N \rightarrow \ell_\alpha\phi)e^{-M_1/T} < H$$

N remaining at temperature T_α when Inverse Decays from flavour α turn off

$$\frac{n_N}{n_\gamma}(T_\alpha) \simeq e^{-M_1/T_\alpha}$$

How big a lepton asymmetry survives ?

1. First produce a population of N_1s, via *e.g.* $(q\ell_\alpha \to N t_R)$ ($\alpha =$ lepton flavour).
   Assume $\Gamma_{prod} \gg H_U$ (timescale for production interactions is shorter than the age of the U)
   $\Rightarrow$ produce the (maximal) thermal population $n_N \simeq n_\gamma$ at $T \gtrsim M_1$, and
   $\Rightarrow$ wipe out any asymmetry in Standard Model leptons

2. Once $T < M_1$, N_1 population decays away ($n \propto e^{-M/T}$).
   Produce a lepton asymmetry in the decays of N_1.
   The lepton asym in flavour α (produced from N_1 decay) can survive *after* Inverse Decays from flavour α turn off ($\Gamma_{ID}(\ell_\alpha \phi \to N) < H_U$)

$$\Gamma_{ID}(\ell_\alpha \phi \to N) \simeq \Gamma(N \to \ell_\alpha \phi) e^{-M_1/T} < H_U$$

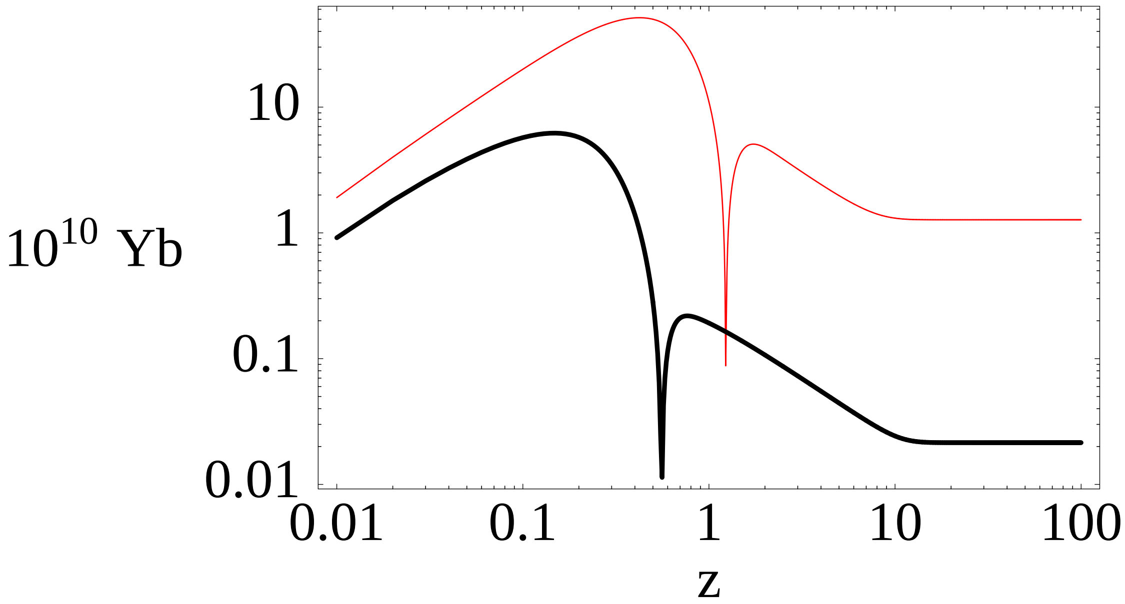
At temperature T_α when Inverse Decays from flavour α turn off,

$$\frac{n_N}{n_\gamma}(T_\alpha) \simeq e^{-M_1/T_\alpha} \simeq \frac{H}{\Gamma(N \to \ell_\alpha \phi)} \quad \text{can calculate this}$$

so (1/3 is from SM $\not{B}\!+\!\not{L}$, $s \sim g_* n_\gamma$, $\epsilon_{\alpha\alpha}$ CP asym in decay)

$$\frac{n_B - n_{\bar{B}}}{s} \sim \frac{1}{3} \sum_\alpha \frac{n_{\ell_\alpha} - n_{\bar{\ell}_\alpha}}{n_N} \frac{n_N(T_\alpha)}{g_* n_\gamma} \sim \frac{1}{3} \sum_\alpha \epsilon_{\alpha\alpha} \frac{H}{g_* \Gamma(N \to \ell_\alpha \phi)}$$

Does it work?



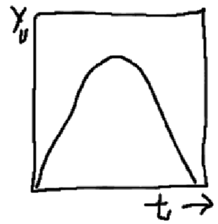
The baryon to entropy ratio, as a function of "time", in flavoured and unflavoured calculation, $\sim$ normalised to observed value. $M_1 = 10^{10}$ GeV.

$\epsilon_{\tau\tau} = 2.5 \times 10^{-6}$, $\epsilon_{\hat{\mu}\hat{\mu}} = -2 \times 10^{-6}$, $\frac{\Gamma_\tau}{H} \simeq 10$, $\frac{\Gamma_{\hat{\mu}}}{H} \simeq 30$

Quelques Précisions

Why Washout matters in *Thermal* Leptogenesis

(ν_R are made by scattering in thermal bath, via Yukawa coupling)



- a population of (the lightest) ν_Rs is produced via its Yukawa coupling (eg $qt^c \rightarrow \nu_R \ell_\alpha$, $\phi\ell_\alpha \rightarrow \nu_R$).
- Population later disappears via same Yukawa coupling (eg. $\nu_R \rightarrow \phi\ell_\alpha$...)
- there is CP violation in production and disappearance...
  $\Rightarrow$ asymmetry in lepton number made with the ν_R is exactly opposite to asymmetry made when ν_R go away (In the case I calculated)
  $\Rightarrow$ thermal leptogenesis "works", because there are Yukawa interactions of the ν_R (eg inverse decays $\phi\ell_\alpha \rightarrow \nu_R$) between production and disappearance of ν_R population, call these interactions **washout**. They deplete the lepton asymmetry made with the ν_Rs.

  For instance, when ν_R interactions are fast, washout is effective, and the asym made with ν_Rs is completely destroyed.

Where do Boltzmann Equations come from?

1. make them up?
2. derive them?

... Stodolsky...
...Dolgov...
Shaposhnikov

(An approach to) Deriving Boltzmann Equations?

1. second quantise your fields
2. write an equation for the number operator:
3. do perturbative expansion in the interaction Hamiltonian....

equations for "density matrices"
allows for oscillations, describes decoherence...

= perturbation theory without Feynman diagrams

Guessing Boltzmann Equations?

1. select interactions as in "effective field theory":
   (a) fast interactions, $\Gamma \gg H$ should be "resummed":
       impose chemical/thermal equilibrium distributions
   (b) slow interactions, $\Gamma \ll H$, can neglect
   (c) relevant interactions, $\Gamma \sim H$, include in BE
2. write equations for the "relevant", comoving, number densities

Guessing Boltzmann Equations?

1. do "effective field theory":
   (a) fast interactions, $\Gamma \gg H \simeq 10T^2/m_{pl}$ should be "resummed": impose chemical/thermal equilibrium distributions
   gauge interactions $\Rightarrow$ thermal (Boltzmann) distributions for all but N_1. Allows to write BE for total number densities, rather than $f(|\vec{p}|)$.
   yukawa interactions $\Gamma \sim \alpha\, y^2 T$: faster, relative to H, as T drops. Chemical equilibrium conditions (at $T \sim 10^{10}$ GeV):

$$\mu_t = \mu_\phi + \mu_{q3} \quad , \quad \mu_b = -\mu_\phi + \mu_{q3} \quad \ldots \qquad , \quad \mu_\tau = -\mu_\phi + \mu_{\ell_3} \quad , \quad \mu_\mu = -\mu_\phi + \mu_{\ell_2}$$

   (b) slow interactions, $\Gamma \ll H$, can neglect
   such as y_e: any asymmetry in e_R is decoupled from rest of bath til $T \sim 10^4 - 10^5$ GeV
   (c) relevant interactions, $\Gamma \sim H$, include.
   Yukawa-mediated decays, inverse-decays (+scattering) of the N_1
2. write equations for relevant co-moving number densities:

$$y_N \equiv \frac{n_{N_1}}{n_{N_1}^{eq}} \quad , \quad y_{\Delta\alpha} \equiv \frac{n_{\ell\alpha} - n_{\overline{\ell\alpha}}}{n_\ell^{eq}} \quad , \quad z \equiv \frac{M_1}{T}$$

Buchmuller, Plumacher, + Di Bari
Nardi etal
Abada etal

Boltzmann Equations

Boltzmann Eqns for N_1

$$\frac{dy_N}{dz} = -\frac{z}{n_N^{eq} H}(y_N - 1)\gamma$$

$y_N = n_N/n_N^{eq}$ pushed to equilibrium by $\gamma(z)$, which describes thermally averaged N decays (D), scatterings (S), inverse decays(ID).

Boltmann Eqns for the lepton asymmetry:
But...?need an eqn per lepton flavour α, or total L? Try both and compare. In flavour α:

$$\frac{d}{dz}\frac{n_{\ell_\alpha} - n_{\bar{\ell}_\alpha}}{n_{\ell_a}} \equiv \frac{dy_{\Delta\alpha}}{dz} = \frac{z}{n_{\ell_\alpha} H(M)}\left[(y_N - 1)\,\epsilon^{\alpha\alpha}\gamma - \gamma^{\alpha\alpha} y_{\Delta\alpha}\right]$$

asym $y_{\Delta\alpha}$ produced by out-of-equilibrium Ns, washed out by same processes D, ID, S.

NB tension: $\gamma \gg Hn^{eq}$ to ensure $y_N \sim 1$ at $T \gtrsim M_1$. But $\gamma \ll Hn^{eq}$ to minimise washout of $y_L^{\alpha\alpha}$.

So Boltzmann Eqns for total lepton number are...

Sum up the flavoured BEs:

$$\sum_\alpha \frac{d}{dz} y_{\Delta\alpha} = \frac{z}{n^{eq}H}\left[\gamma\,(y_N - 1)\underbrace{(\epsilon^{ee} + \epsilon^{\mu\mu} + \epsilon^{\tau\tau})}_{\epsilon} - \underbrace{(\gamma^{ee} y_{\Delta e} + \gamma^{\mu\mu} y_{\Delta\mu} + \gamma^{\tau\tau} y_{\Delta\tau})}_{\neq \gamma y_\Delta}\right]$$

$$= \frac{z}{n^{eq}H}\left[(y_N - 1)\,\epsilon\gamma - \left(\gamma^{ee} y_{\Delta e} + \gamma^{\mu\mu} y_{\Delta\mu} + \gamma^{\tau\tau} y_{\Delta\tau}\right)\right]$$

Compare to the usual "single flavour" approx= consider lepton number, neglect flavour

$$\frac{dy_\Delta}{dz} = \frac{z}{n^{eq}H}\left[(y_N - 1)\,\epsilon\gamma - (\gamma^{ee} + \gamma^{\mu\mu} + \gamma^{\tau\tau})\left(y_{\Delta e} + y_{\Delta\mu} + y_{\Delta\tau}\right)\right]$$

NOT the same

Abada etal
Nardi etal

$\Rightarrow$ careful about which species are distinct, when sum probabilities vs amplitudes, etc

where $z = \frac{M_1}{T}$ is a time var, $\gamma^{\alpha\alpha} = \gamma_D^{\alpha\alpha} + \gamma_{\Delta L=1}^{\alpha\alpha}$ is $N \leftrightarrow H\ell_\alpha$ and $qt^c \leftrightarrow N\ell_\alpha$ etc rates, $\gamma = \sum_\alpha \gamma^{\alpha\alpha}$, $y_N = n_N/n_N^{eq}$...

Summary: a fairy tale for physicists

Once upon a time, a Universe was born. (Maybe ours?)

At the christening of the Universe, the Standard Model and the Seesaw (heavy sterile N_j with $\not{L}$ masses and $\not{CP}$ interactions) were among the gifts given by the good fairies to the Universe.

The adventure begins after inflationary expansion of the Universe:

1. Assuming its hot enough, a population of N_1 appear, because they like the heat.

2. As the temperature drops below M_1, the N_1 population decays away.
3. In the $\not{CP}$ and $\not{L}$ interactions of the N, an asymmetry in SM leptons is created.

4. If this asymmetry can escape the big bad wolf of thermal equilibrium...
5. the lepton asym gets partially reprocessed to a baryon asym by non-perturbative $B+L$ -violating SM processes ("sphalerons")

And the Universe lived happily ever after, containing many photons. And for every 10^{10} photons, there was an excess of 6 baryons (protons or neutrons), with respect to anti-baryons.

Observations that would *support* thermal leptogenesis

Suppose that we DO observe

1. m_ν is majorana from $0\nu2\beta$ expts
   - this is a prediction of the seesaw...

2. $\not{C}\not{P}$ in neutrino oscillations
   - need $\not{C}\not{P}$ in leptons for leptogen

3. SUSY at the LHC, and lepton flavour violation (LFV), like $\mu \to e\gamma$, $\tau \to \mu\gamma$ ...
   - LFV at observable rates is an expectation in the SUSY seesaw. In MSUGRA, these rates give additional information about seesaw parameters

Martin+Ringeval

4. ? can T_{reheat} be measured? (CMB ? : amplitude, tensor/scalar ...
   - If $T_{reheat} > 10^9$ GeV, consistent with the thermal leptogenesis with $M_1 \ll M_2 \ll M_3$

But what if...

1. m_ν is Dirac ($e.g.$ inverse hierarchy and no $0\nu 2\beta$)
   - hmm. Minimal Type 1 seesaw scenario is dead.
     But there is Dirac leptogenesis....

2. no $\not{C}\not{P}$ in neutrino oscillations
   - but there are 6 phases in the seesaw, always possible to arrange unmeasurable phases to get big enough asym.

3. SUSY at the LHC, but no lepton flavour violation (LFV), such as $\mu \to e\gamma$, $\tau \to \mu\gamma$ ...
   - can (probably) fit the SUSY seesaw and working leptogenesis, to all LFV observations

4. $T_{reheat} \ll 10^9$ GeV
   - thermal leptogenesis with $M_1 \ll M_2 \ll M_3$ scenario is dead.
     But...leptogenesis with degenerate M_i works at an temperature...

5. space has 4+n dimensions at a scale $< M_1 \sim 10^{10}$ GeV
   Or what if the Higgs is composite?
   ...

Minkowski, Yanagida
Gell-Mann Ramond Slansky

The See-Saw ("type 1", 3 N_i)

• in the charged lepton ("flavour") and $N(= \nu_R)$ mass bases, at energy scale $> M_3 > M_2 > M_1 \sim 10^{10\pm1}$ GeV:

18 **new** parameters chez les leptons:
M_1, M_2, M_3
18 - 3 (ℓ phases) in λ

$$\mathcal{L} \;=\; \mathcal{L}_{SM} + \lambda_{\alpha k} \overline{N}_k \ell_\alpha \cdot \phi - \frac{1}{2} \overline{N_j}^c M_j N_j$$

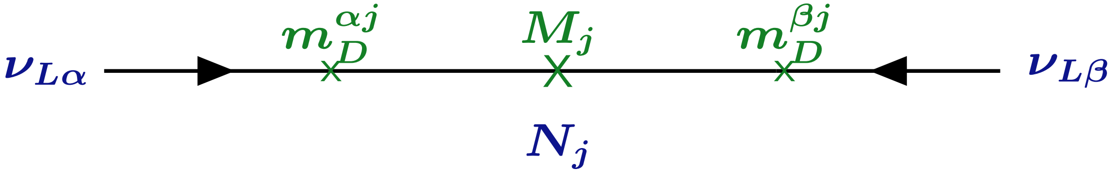
NB: lepton number not conserved (if N a lepton, M is $\not{L}$), and $\not{CP}$ in λ.

• at the weak scale, get effective light neutrino mass matrix

9 **new** parameters:
m_1, m_2, m_3
6 in U

$$[m_\nu] = U D_m U^T \;=\; \lambda M^{-1} \lambda^T v_u^2 \,, \qquad v_u = \langle H_u^0 \rangle$$

$$m_3 \;\sim\; \frac{m_t^2}{10^{14} GeV} \sim .1 eV$$



9 param in slepton mass matrix $\Rightarrow$?reconstruct the seesaw dans le meilleur des mondes MSUGRA ?
Mais... careful about prior dependence of claimed correlations between observables in MSUGRA seesaw ...(scanning 14-dim parameter space)...