Neutrino Mass Mechanisms and Leptogenesis

1. neutrino masses (majorana or dirac) and mixing angles

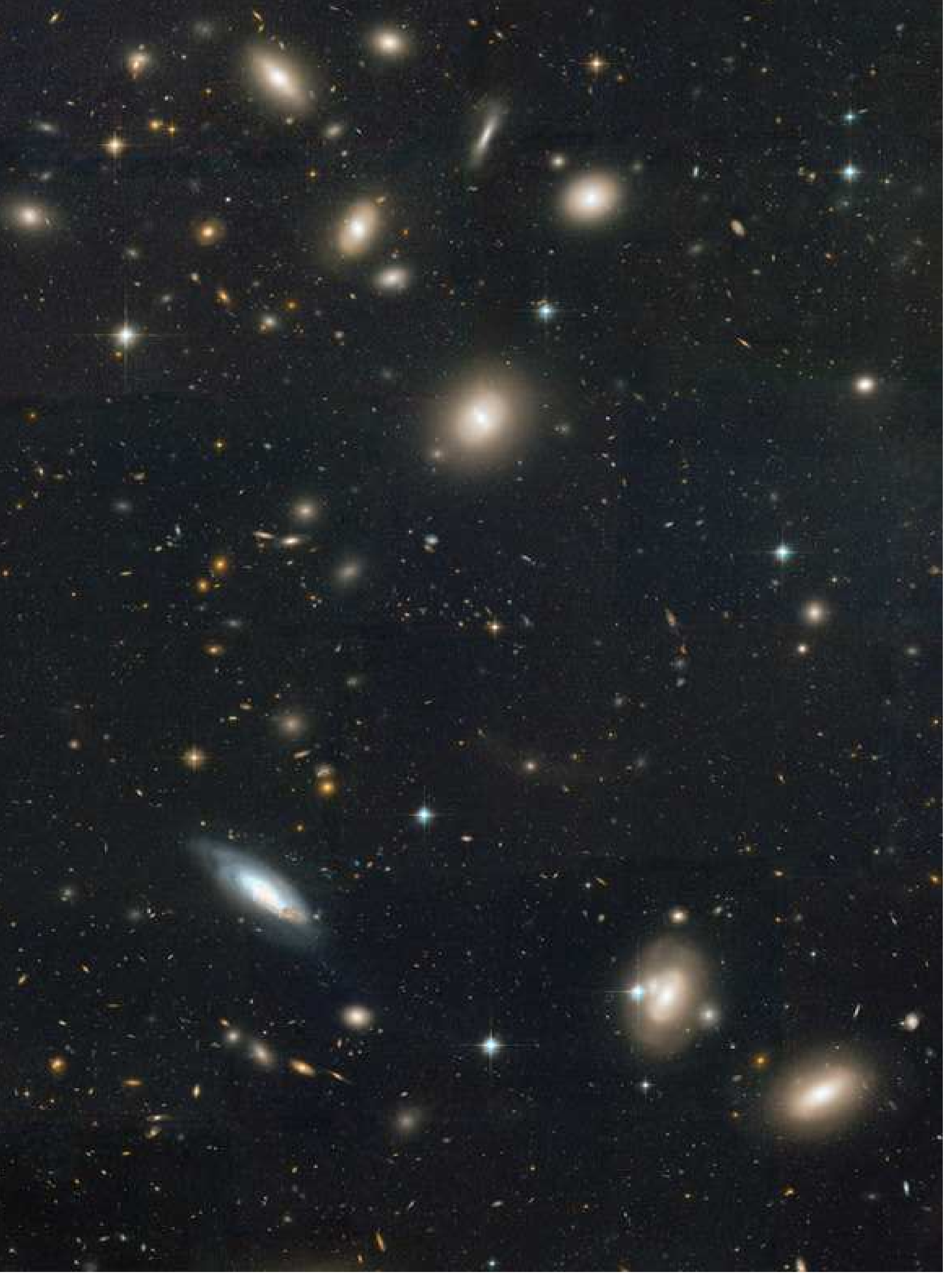
2. mechanisms for small Dirac masses

3. mechanisms for small Majorana masses

    - suppressed by a large mass scale and small couplings: the seesaw
    - suppressed by small couplings and loops: R_p violation in SUSY

4. **leptogenesis**

    - **required ingredients for baryogenesis**
    - **baryogenesis via leptogenesis**
    - **flavoured thermal leptogenesis** **type I seesaw, hierarchical N_i**



The Baryon Asymmetry of 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)

$\Rightarrow$ there is an excess of matter over anti-matter in the Universe.

matter $\simeq H = p + e^-$, so this implies a baryon asymmetry :

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

(not worry about lepton asymmetry, because there is an undetectable C(M)B of νs, which could contain a large asymmetry.)

could the Universe have been *born* with a baryon asymmetry?
No: asymmetry exponentially diluted during inflation (required for $\Delta T/T$).

$\Rightarrow$ we must create the asymmetry after inflation

parenthese: how to *measure* $Y_B = (n_B - n_{\bar{B}})/n_\gamma$?

n_γ photon number density, from CMB.

- luminous matter — we see it.
- BBN
  - baryons rare $\longrightarrow$ make nucleons in 2-body processes,
  - density of De ($E_{bind} \sim$ 2.2 MeV) develops *when not disassociated by energetic γ from Boltzmann tail:*

$$n_B - n_{\bar{B}} \gtrsim n_\gamma(E > 2.2\text{MeV}) \sim E^3 e^{-2.2MeV/T_{BBN}} \Rightarrow -\ln Y_B \sim 2.2MeV/T_{BBN}$$

  - at $T_{BBN} \sim .1\text{MeV}$, make De with all available n, then ^{4}He with all available De
  - (but n are decaying to p, $\tau_n \sim 10$ minutes, $\tau_U \sim (T/MeV)^2$ seconds)
  - amount of $^4He \longrightarrow$ temperature of BBN $\longrightarrow n_B - n_{\bar{B}}$
- CMB most accurate
  - before recombination, within horizon, photon-baryon fluid oscillates (sound waves). These are the peaks in the C_ℓ plots.
  - amplitude of oscillation $\leftrightarrow$ baryon density
  - $\Rightarrow$ height of first peak related to Y_B.

Required ingredients to make a baryon asymmetry

1. B violation
   if Universe ($\equiv U$) starts in state of $n_B - n_{\bar{B}} = 0$, need $\not{B}$ to evolve to $n_B - n_{\bar{B}} \neq 0$
2. C and CP violation
   if U starts in CP eigenstate, need $\not{CP}$ in evolution to obtain excess of particles over anti-particles

3. out-of-thermal-equilibrium dynamics
   equilibrium $=$ static, no asymmetries in unconserved quantum numbers

in the Standard Model???

2. C and CP violation — in the CKM matrix
3. out-of-thermal-equilibrium dynamics — U(niverse) is expanding and cooling, so $\not{TE}$ from

- slow interactions : $\tau_{int} \gg \tau_U$ $(\Gamma_{int} \ll H)$

$$but\ldots \qquad \Gamma_{decay} \sim \frac{\lambda^2 M}{8\pi} \qquad\qquad H \sim \frac{T^2}{m_{pl}} \sim 10^{-17} T|_{T=m_W}$$

- phase transitions: the electroweak phase transition

B+L violation in the Standard Model

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

...BUT: your friend the axial anomaly, who gives $\pi^0 \to \gamma\gamma$, also gives $\not{B} + \not{L}$ interactions that are fast at $T > m_W$. In field theory of massless chiral fermions:

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

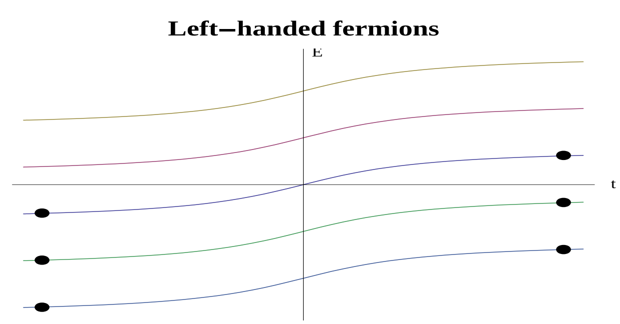
For LH SU(2) doublet ψ_L^i of the SM:

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

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

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

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



$t \longrightarrow$

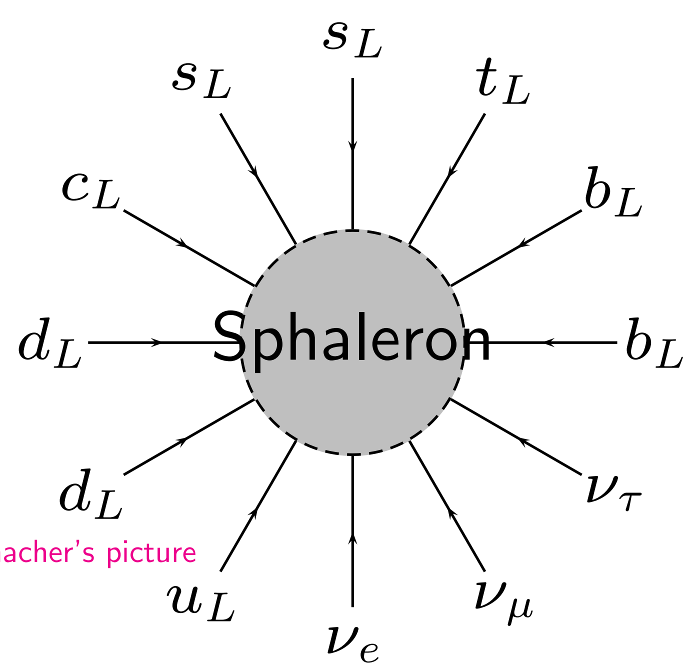
SM B+L violation : rates

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... (? maybe no barrier above EPT?)



Plumacher's picture

$$\Gamma_{B+L} \sim \begin{array}{ll} \alpha^5 T & T > EWPT \\ e^{-m_W/T} & T < EWPT \end{array}$$

IN equilibrium after the SM electroweak phase transition

no EW baryogenesis in the standard model

but fast SM $\not{B}$ at $T > EPT$

summary, caveats

- 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 ($\not{B}$, $C\not{P}$, $\not{T}E$) are present in the SM (of part phys and cosmo)...but *don't* make a baryon asymmetry.
- $\Rightarrow$ we need Beyond the Standard Model physics ! ...but... recreational phenomenology? any extension of the SM has many free parameters, could always tune to get Y_B?
- *pas aussi facile que ça*: other constraints on $\not{B}$, $C\not{P}$, $\not{T}E$
  eg proton lifetime: $\tau_p \gtrsim 10^{32}$ yrs
  timescale for baryogenesis: $\tau_U \simeq \begin{array}{l} 10^{-10}\ sec\ \ (\mathrm{EWPT}) \\ 1\ sec\ \ (\mathrm{nucleosynthesis}) \end{array}$

$\Rightarrow$ we would like : BSM physics that is otherwise motivated (data, theoretically attractive), and generates the baryon asymmetry without making the proton decay ($e.g.$ "sphalerons").

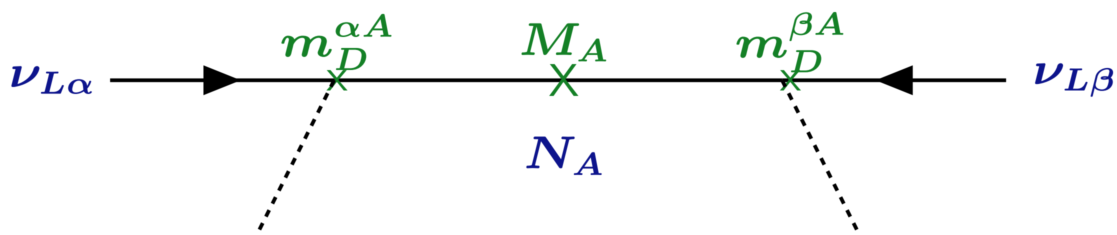
$\Rightarrow$ *THE (SUSY) SEESAW*

The See-Saw in three generations

- in the charged lepton ("flavour") and $N(=\nu_R)$ mass bases, at large energy scale $\gg M_i$:

21 parameters chez les leptons:
$m_e, m_\mu, m_\tau, M_1, M_2, M_3$
18 - 3 (ℓ phases) in λ

$$\mathcal{L} = \mathcal{L}_{SM} + \lambda^*_{\alpha J} \overline{\ell}_\alpha \cdot H N_J - \frac{1}{2} \overline{N_J} M_J N_J^c$$



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

12 parameters:
$m_e, m_\mu, m_\tau, m_1, m_2, m_3$
6 in U_{MNS}

$$\lambda M^{-1} \lambda^{\mathbf{T}} \langle H^0 \rangle^2 = [m_\nu] = U^* D_m U^\dagger$$

The Matter Excess of the Universe—Leptogenesis

Recall: required ingredients:
- C and CP violation (complex $[\lambda]$)
- non-equilibrium dynamics ($\Gamma_N < H$)
- baryon number violation ($\not{L}$, $\not{B} + \not{L}$)

three steps:

1. **dynamics** produce some number density of N, who later ($T \lesssim M_1$) decay
2. If the N interactions are **CP** violating, a lepton asymmetry Y_L may be produced
3. non-perturbative $\not{B} + \not{L}$ SM processes: lepton asymmetry $\longrightarrow$ baryon asymetry.

many implementations:

- thermal leptogenesis with hierarchical M_J: $M_1 \ll M_{2,3}$
- thermal leptogenesis with quasi-degenerate M_J ($\not{CP}$ in mixing)
- "soft leptogenesis" ($\tilde{N}$ decay, soft SUSY terms give $\not{CP}$ in mixing $\tilde{N}_J - \tilde{N}_J^*$)
- a la Affleck Dine (classical field evolution in the early U)
- non-thermal N production (from inflaton decay, in preheating, ...)
- ...also Dirac leptogenesis...
- ...

... falsifiable ???

Another tangent: why hierarchical N_J?

In the (type 1) seesaw:

$$[m_\nu] = [\lambda]^T [M]^{-1} [\lambda] v_u^2$$

take determinants:

$$m_3 m_2 m_1 = \frac{\lambda_1^2 \lambda_2^2 \lambda_3^2}{M_1 M_2 M_3} v_u^6$$

- assume a steep hierarchy in the Yukawas $\lambda_3 \sim 1$, $\lambda_2 \sim 10^{-2}$, $\lambda_1 \sim 10^{-4}$

$$m_3^3 \frac{m_2}{m_3} \frac{m_1}{m_3} = \frac{10^{-12}}{\frac{M_1}{M_3}\frac{M_2}{M_3} M_3^3} v_u^6$$

- assume that (!) $m_3 \sim v_u^2/M_3$ is natural

$$\frac{m_2}{m_3}\frac{m_1}{m_3} = \frac{10^{-12}}{\frac{M_1}{M_3}\frac{M_2}{M_3}}$$

- assume $m_1 \gtrsim .1 \div .01 m_2$ (not $\sim 10^{-10} m_2$)

$$.1 \frac{m_1}{m_3} = \frac{10^{-12}}{\frac{M_1}{M_3}\frac{M_2}{M_3}}$$

...so to get mild hierarchy in m_i, given steep hierarchy in λ_i and degenerate M_J...requires a "conspiracy" in RH sector (eg $\pi/4$ mixing angles)

Thermal leptogenesis with hierarchical N_i

Fukugita Yanagida
...

After inflation, vaccuum energy density is transfered to a hot thermal soup at T_{reheat}, containing particles with gauge interactions (no N_i). Then...

1. somehow produce some number density Y_{N_1} of N_1 (helpful to have $M_1 \lesssim T_{reheat}$).
   Later (once $Y_{N_1} \simeq Y_{N_1}^{eq}$), the N_1 will decay away. $\Leftrightarrow \eta_\alpha$
2. If the N_1 decay is $\not{C}\not{P}$: $\Gamma(N_1 \to H\ell_\alpha) - \Gamma(N_1 \to \overline{H\ell}_\alpha) \neq 0$, an asymmetry in L_α can be produced $\Leftrightarrow \epsilon_{\alpha\alpha}$
   If inverse decays are "out of equilibrium", the asymmetry could survive. $\Leftrightarrow \eta_\alpha$
3. SM non-perturbative $\not{B} + \not{L}$ partially transforms lepton asym $\longrightarrow$ baryon asym. $\Leftrightarrow C$

Usual parametrisation (s = entropy density))

$$\left(\frac{n_B - n_{\bar{B}}}{s} =\right) \qquad Y_{\Delta B} = \frac{n_N^{eq}(T \gg M_1)}{s} \sum_\alpha \frac{n_{\ell_\alpha} - n_{\bar{\ell}_\alpha}}{n_N} \times \eta_\alpha \times C.$$

$$\sim 4 \times 10^{-3} \sum_\alpha \epsilon_{\alpha\alpha} \times \eta_\alpha \times \frac{1}{3}$$

$$\sim 8 \times 10^{-11}$$

η parametrises difficulty of obtaining initial thermal number density, and out-of-equilibrium decay....

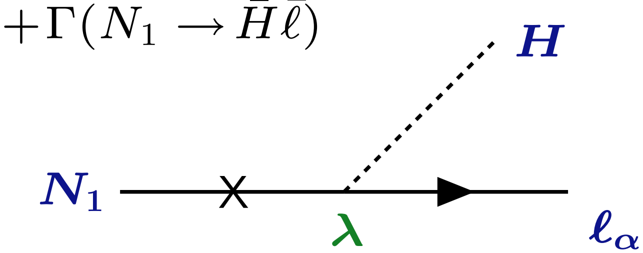
Step 2: $\not{C}\not{P}$ and ϵ

Covi et al
...

After inflation, vaccum energy density is transfered to a hot thermal soup at T_{reheat}. Then...

1. Suppose a distribution of N_1 (and $\tilde{N}_1$) is produced, then decays away (as $T \lesssim M_1$). Departure from equilibrium required — more later.
2. If there is $\not{C}\not{P}$ in decays ($\not{L}$ from M), can produce asymmetries in lepton flavours:

$$\frac{n_{\ell_\alpha} - n_{\bar{\ell}_\alpha}}{n_N} \simeq \epsilon_{\alpha\alpha} = \frac{\Gamma(N_1 \rightarrow H\ell_\alpha) - \Gamma(N_1 \rightarrow \bar{H}\bar{\ell}_\alpha)}{\Gamma(N_1 \rightarrow H\ell) + \Gamma(N_1 \rightarrow \bar{H}\bar{\ell})}$$



To obtain $\Gamma - \bar{\Gamma} \neq 0$, need **Im** { coupling constants c} $\times$ **Im** { "amplitude" $\mathcal{A}$}.

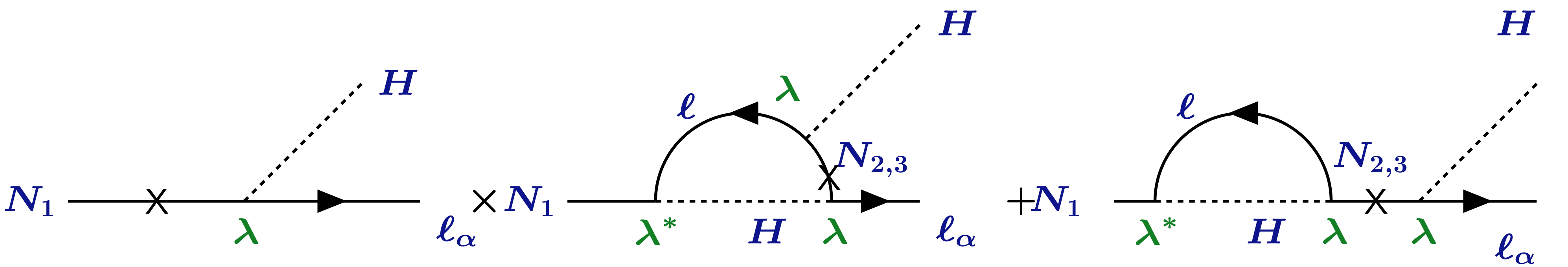
Write tree + loop: $\mathcal{M} = c_0\mathcal{A}_0 + c_1\mathcal{A}_1$ $\qquad$ $\overline{\mathcal{M}} = c_0^*\mathcal{A}_0 + c_1^*\mathcal{A}_1$ (sloppy)

$$\Rightarrow \int d(phase\ space)|\left(\mathcal{M}|^2 - |\overline{\mathcal{M}}|^2\right) \propto \mathrm{Im}\{c_0 c_1^*\}\mathrm{Im}\{\mathcal{A}_0\mathcal{A}_1^*\}$$

Im { $\mathcal{A}$ } $\Leftrightarrow$ on-shell intermediate particles in a loop:

Guestimating $\epsilon_{\alpha\alpha}$

$\not{L}$ in N_1 decays from $\{\lambda, M\}$, and $\not{CP}$, allows to produce asymmetry $\epsilon_{\alpha\alpha} \simeq (n_{\ell_\alpha} - n_{\bar{\ell}_\alpha})/n_N$:



$$\epsilon_{\alpha\alpha} = \frac{\Gamma(N_1 \to H\ell_\alpha) - \Gamma(N_1 \to \bar{H}\bar{\ell}_\alpha)}{\Gamma(N_1 \to H\ell) + \Gamma(N_1 \to \bar{H}\bar{\ell})} \simeq \frac{-3M_1}{8\pi[\lambda^\dagger\lambda]_{11}} \mathrm{Im}\left[[\lambda^T \frac{[m_\nu]^*}{v_u^2}]_{1\alpha}\lambda_{\alpha 1}\right]$$

$$< \frac{3}{8\pi}\frac{M_1 m_{\nu,max}}{v_u^2}$$

DavidsonIbarra
HamaguchiMurayamaYanagida

lower bound on $M_1 \gtrsim T_{reheat}/5$ to get a big enough asymmetry:

$$M_1 \gtrsim 10^9 \mathrm{GeV} \qquad \text{gravitinos!?}$$

Non-equilibrium...

Recall the scenario:

1. **somehow produce some number density Y_{N_1} of N_1 (helpful to have $M_1 \lesssim T_{reheat}$). Later (once $Y_{N_1} \simeq Y_{N_1}^{eq}$), the N_1 will decay away.**
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   If inverse decays are "out of equilibrium", the asymmetry could survive.
3. SM non-perturbative $\not{B} + \not{L}$ partially transforms lepton asym $\longrightarrow$ baryon asym.

- N_1 is gauge singlet, produced and decays via Yukawa λ.
  $\Gamma_{prod} \sim h_t^2 \lambda^2 T > H(T \sim M_1)$ to reach $n_N \sim n_\gamma$
  $\Gamma_{dec} \sim \lambda^2 T < H(T \lesssim M_1)$ to have out of equilibrium decay

  Buchmuller Plumacher

  $$\Rightarrow \ DOES\ IT\ WORK?? \qquad Yes! \Rightarrow \ Boltzmann Eqns$$

- "washout" interactions ($e.g.$ $H\ell_\alpha \to N_1$, they eat the asym), are required for thermal leptogenesis. Their strength is different for different lepton flavours

  $$\Rightarrow FLAVOURED\ LEPTON\ ASYMS$$

  Nardi et al
  Davidson etal

unflavoured: Fukugita Yanagida
Buchmuller et al,
Giudice et al...
with flavour: Barbieri etal
Endoh etal, Vives, Pilaftsis Underwood
Abada etal, Nardi etal, ...

Non equilibrium (η) and why a Boltzmann code

1. produce the (maximal) thermal density $n_N \simeq n_\gamma$ if ($M_1 \lesssim T$, and) production rate, $e.g.$ $\Gamma(q_L t_R^c \to \phi \to \ell N)$ is fast enough ($\tau_{prod} < \tau_U$):

$$\Gamma_{prod} \sim \frac{h_t^2 [\lambda\lambda^\dagger]_{11}}{4\pi} T > H, \quad \Rightarrow \quad \frac{[\lambda\lambda^\dagger]_{11}}{4\pi} > \left. \frac{10T}{m_{pl}} \right|_{T=M_1}$$

Can show: $\frac{[\lambda\lambda^\dagger]_{11} v_u^2}{M_1} = \tilde{m}_1 > m_1$. "Expect" $\tilde{m}_1 \gtrsim m_{sol}$, $\Rightarrow \Gamma_{prod} \simeq \Gamma_{decay} \gg H$

need Boltzman code... but here make analytic estimates...

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Non equilibrium (η)

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need Boltzman code... but here make analytic estimates...

2. The lepton asym in flavour α (produced from N decay) can survive after Inverse Decays from flavour α turn off ($\tau_{ID} > \tau_U$)

$$\Gamma_{ID,\alpha} \equiv \Gamma(\ell_\alpha \phi \to N_1) \simeq \Gamma_{decay}(N_1 \to \ell_\alpha H) e^{-M_1/T} \simeq \frac{|\lambda_{\alpha 1}|^2 M_1 e^{-M_1/T}}{8\pi} < \frac{10T^2}{m_{pl}}$$

Then, at temperature $\equiv T_\alpha$ when Inverse Decays from flavour α turn off,

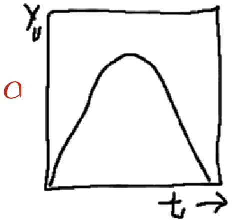
$$\frac{n_N}{n_\gamma}(T_\alpha) \simeq e^{-M_1/T_\alpha} \simeq \frac{H}{\Gamma(N_1 \to \ell_\alpha \phi)} \equiv \eta_\alpha$$

so, if have CP asym $\epsilon_{\alpha\alpha} \neq 0$, $\epsilon_{\beta\beta} = 0$:

$$Y_B \sim \frac{1}{3} \frac{n_{\ell_\alpha} - n_{\bar{\ell}_\alpha}}{n_N} \frac{n_N(T_\alpha)}{n_\gamma} \sim \frac{1}{3} \epsilon_{\alpha\alpha} \frac{H}{g_* \Gamma_{decay}(N_1 \to \ell_\alpha \phi)}$$

(sum over flavour in general case)

Non-equilibrium: why/when Flavour Asymmetries L_α



- a population of (the lightest) ν_Rs is produced via its Yukawa coupling (eg $qt^c \to \nu_R \ell_\alpha$, $\phi \ell_\alpha \to \nu_R$).
- Population later disappears via same Yukawa coupling (eg. $\nu_R \to \phi \ell_\alpha$...)
- 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 $\phi \ell_\alpha \to \nu_R$ 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.

• flavour matters, because washout does: initial state for washout interactions contains a SM LH lepton, so must know *are leptons distinguishable?*

compare rates for charged lepton Yukawas h_τ, h_μ to $H, \Gamma(\nu_R \to \ell\phi)$.
If "in equilibrium", Yukawas contribute to "thermal masses" $\Leftrightarrow$ distinguish flavours

$$\Gamma_\tau \simeq 10^{-2} h_\tau^2 T > H \text{ for } T < 10^{12} \text{ GeV}, \quad \Gamma_\mu > H \text{ for } T < 10^9 \text{ GeV}$$

In washout rates:
distinguishable $\Rightarrow$ sum probabilities
indistinguishable $\Rightarrow$ sum amplitudes

What changes *phenomenologically*, including flavour?

"single flavour" approx, successful thermal leptogenesis $\Rightarrow$ light ν mass scale $\lesssim .1$ eV.

"flavoured": more $C\!\!\!/P$, so no bound. Models can be tuned to work for $m_\nu \lesssim$ few eV (cosmo)

There is an envelope, in space of parameters leptogenesis depends on $(M_1,\ \Gamma,\ \epsilon...)$ where leptogenesis *can* work.

Including flavour gives envelope more dimensions $(M_1, \epsilon_{\alpha\alpha}, \Gamma_{\alpha\alpha})$, little changes to " interesting" regions of the envelope projected onto M_1, Γ space (not move lower bound on T_{reheat})

Antusch+..
Blanchet+..

Josse-Michaux+...

"single flavour": no model-indep connection between $C\!\!\!/P$ for leptogenesis and MNS phases.

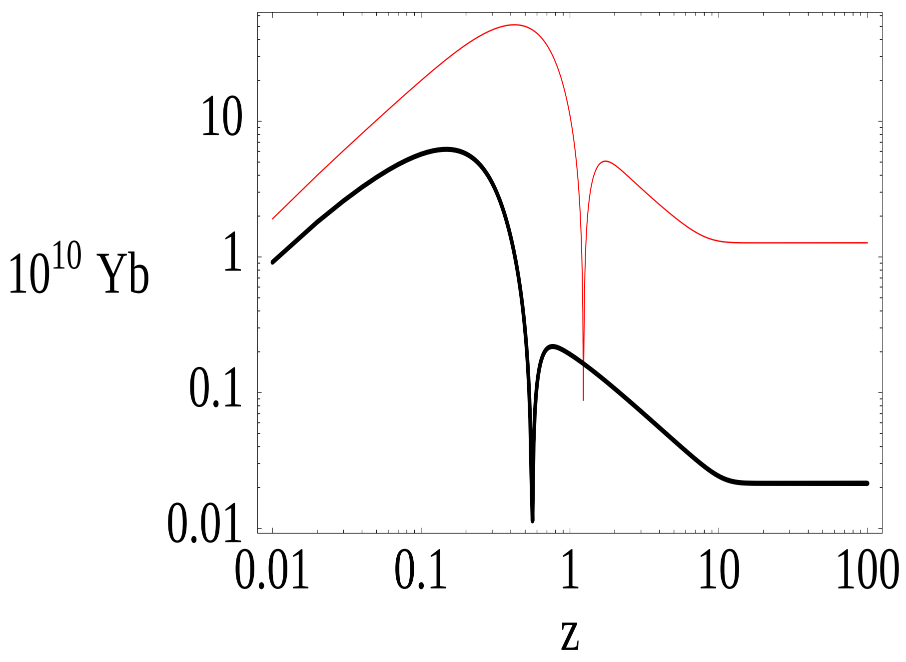
Fujihara+...

"flavoured": still no sensitivity of baryon asym. to MNS phases (but can say things in classes of models)

Antusch+..
Branco+..

Pascoli+...

But use flavoured estimates to check if your model works...



The baryon to entropy ratio, as a function of "time", in flavoured and unflavoured calculation.

$\epsilon_{\tau\tau} = 2.5 \times 10^{-6}$, $\epsilon_{\mu\mu} = -2 \times 10^{-6}$, $\epsilon_{ee} = 10^{-7}$

$M_1 = 10^{10}$ GeV

$\frac{\Gamma_{\tau\tau}}{H} \simeq 10$, $\frac{\Gamma_{\mu\mu}}{H} \simeq 30$, $\frac{\Gamma_{ee}}{H} \simeq 30$

Observations that would *support* thermal leptogenesis

Suppose that we *DO* observe

1. m_ν is majorana from $0\nu 2\beta$ expts
   - this is a prediction of the seesaw...

2. $\not{CP}$ in neutrino oscillations
   - need $\not{CP}$ 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

4. ???can T_{reheat} be measured?
   - 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
   - hmm. "minimal" Type 1 seesaw scenario is dead.
     But there is Dirac leptogenesis. Or, consider more (6?) singlets?

2. no $\not{CP}$ observed 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 fit the SUSY seesaw and working leptogenesis, to all LFV observations

4. ???can T_{reheat} be measured?
   - If $T_{reheat} \ll 10^9$ 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...

Careful about model scans in particle physics papers: endemnic prior dependence...

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.