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

One number: $\left.\frac{n_B - n_{\bar{B}}}{n_\gamma}\right|_0 \simeq 6 \times 10^{-10}$

thanks to W Buchmuller+ C Perrault

Three ingredients: $\not{B}$, $\not{CP}$, $\not{TE}$

...many recipes...

Leptogenesis $\equiv$ *non-equil. generation of* Y_L *"sphalerons" redistribute to* Y_B

Sacha Davidson
IPN de Lyon/CNRS, France

1. a vanilla scenario: type I seesaw
   $\sim$ estimates
   particularities : "washout", and "flavour"

2. can it be tested? or is it a physicists fairytale? There is a wolf...
   usually not (in the forseeable future)

3. can one make reliable predictions?

   ...parrallel sessions:Eijima,Kartavtsev,

Besak/Bodeker/Laine...
Gagnon-Shaposhnikov,...
Beneke etal
et al + Kartavtsev

A Baryon excess today:

$$Y_B \equiv \left.\frac{n_B - n_{\bar{B}}}{s}\right|_0 = 3.86 \times 10^{-9}\Omega_B h^2 \simeq (8.53 \pm 0.11) \times 10^{-11} \qquad (s_0 \simeq 7 n_{\gamma,0})$$

PLANCK

to be produced after inflation (dilutes previous asyms)

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Ingredients to prepare in the early U (old russian recipe)

1. $\not{B}$: required to evolve from $B = 0$ state to $B \neq 0$ state

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3. $\not{TE}$: no asyms in thermal equil. for unconserved Q #s

Present in SM, but hard to combine to give big enough asym Y_B

Cold EW baryogen??
Tranberg et al
...

$\Rightarrow$ *evidence for physics Beyond the Standard Model (BSM)*

One observation to fit, many new parameters...

$\Rightarrow$ *prefer BSM motivated by other data* $\Leftrightarrow m_\nu \Leftrightarrow$ *seesaw!* (uses non-pert. SM $\not{B+L}$)

Minkowski, Yanagida
Gell-Mann Ramond Slansky

The (type I) Seesaw

- add 3 singlet N to the SM in the charged lepton and N mass bases, at energy scale $> M_i$:

add 18 parameters:
M_1, M_2, M_3

$$\mathcal{L} = \mathcal{L}_{SM} + \boldsymbol{\lambda}_{\alpha J} \overline{N}_J \ell_\alpha \cdot \phi - \frac{1}{2} \overline{N_J} M_J N_J^c$$

18 - 3 (ℓ phases) in λ

M_I unknown ($\not\propto v = \langle \phi^0 \rangle$), and Majorana ($\not{L}$). $\not{C}\not{P}$ in complex $\boldsymbol{\lambda}_{\alpha J}$.

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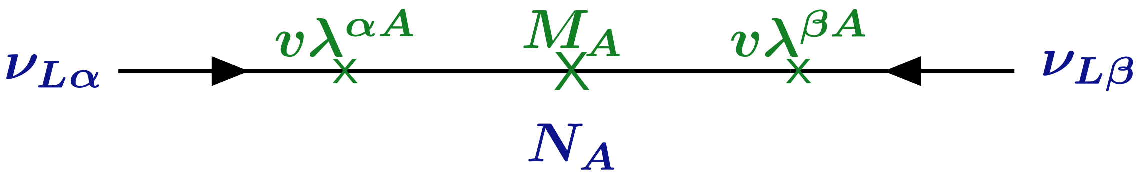
- at low scale, for $M \gg m_D = \lambda v$, light ν mass matrix



9 parameters: m_1, m_2, m_3

6 in U_{MNS}

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

for $\lambda \sim h_t, \quad M \sim 10^{15}$ GeV
$\lambda \sim 10^{-4}, \quad M \sim 10^{7}$ GeV $\quad \sim \quad .05$ eV

"natural" $m_\nu \ll m_f$: $m_\nu \propto \lambda^2$, and $M > v$ allowed.

Minkowski, Yanagida
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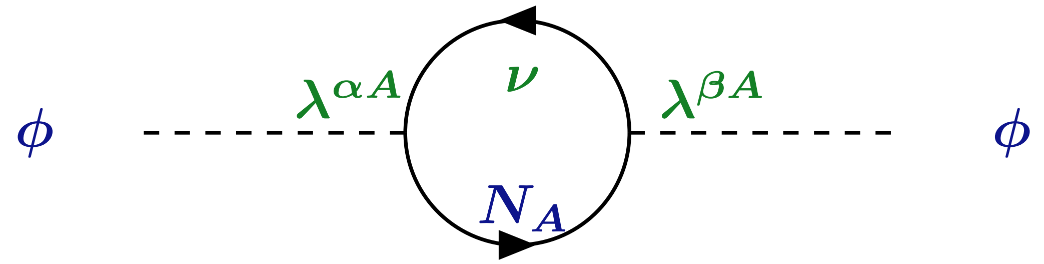
• at low scale,Higgs mass contribution



$$\delta m_\phi^2 \simeq -\sum_I \frac{[\boldsymbol{\lambda}^\dagger \boldsymbol{\lambda}]_{II}}{8\pi^2} M_I^2 \quad \sim \frac{m_\nu M_I^3}{8\pi^2 v^4} v^2$$

$$\text{for } M \gtrsim 10^7 \text{ GeV} \qquad > \quad v^2$$

(can cancel at 1 loop by adding particles) $\Rightarrow$ do seesaw with $M_I \lesssim 10^8$ GeV?
Need a symmetry (SUSY?) to cancel at ≥ 2 loop? ...

(NB, in this talk, ϕ = Higgs, H = Hubble)

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

Leptogenesis in the type 1 seesaw: usually a Fairy Tale

Once upon a time, a Universe was born.

Fairy Godmothers come to the Christening of the Universe

The leptogenesis fairy tale

Once upon a time, a Universe was born.

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

The adventure begins after inflationary expansion of the Universe:

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2. As the temperature drops below M, the N 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...

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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 were 6 extra baryons (wrt anti-baryons).

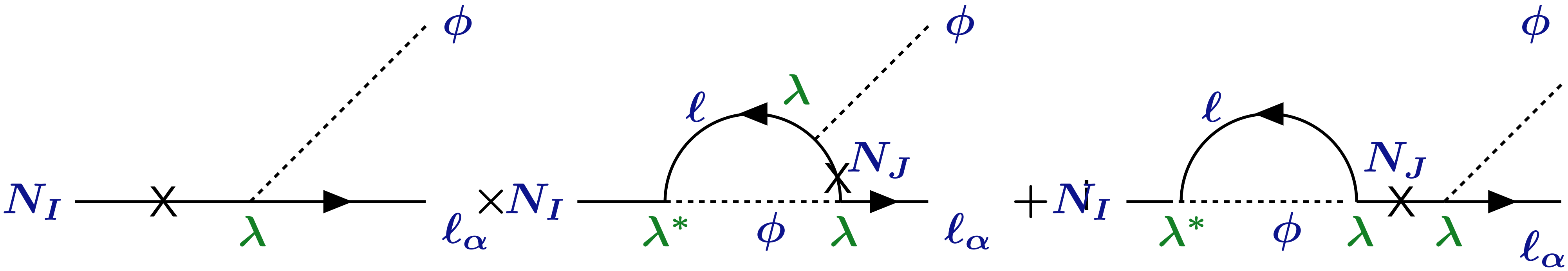
$\not{CP}$ and $\not{L}$

$\not{CP}$, $\not{L}$: N_1 interactions generate an excess of leptons ℓ_α with respect to anti-leptons $\bar{\ell}_\alpha$ ($\not{CP}$ from complex cpling × (tree × on-shell loop)). For instance:

finite temp:Beneke etal 10

$$\epsilon_I^\alpha = \frac{\Gamma(N_I \to \phi \ell_\alpha) - \Gamma(\bar{N}_I \to \bar{\phi}\bar{\ell}_\alpha)}{\Gamma(N_I \to \phi \ell) + \Gamma(\bar{N}_I \to \bar{\phi}\bar{\ell})} \qquad \text{(recall } N_I = \bar{N}_I\text{)}$$

$$\sim \text{ fraction } N \text{ decays producing excess lepton} (\gtrsim 10^{-6})$$



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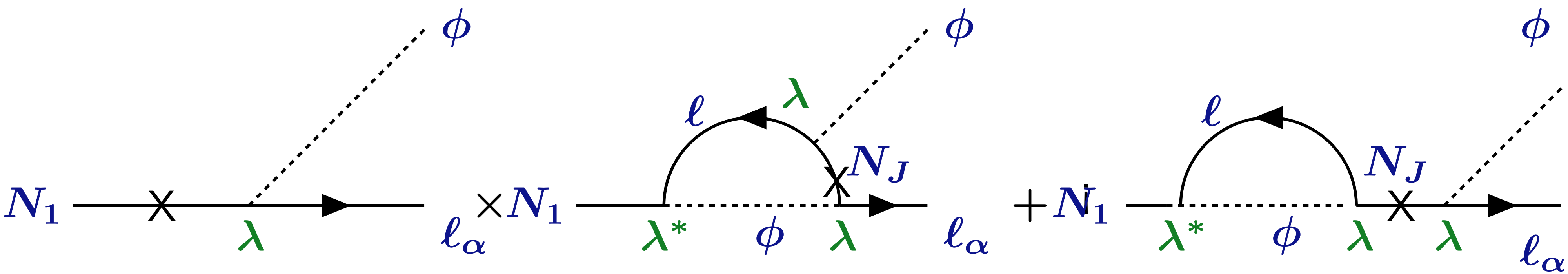
$$\epsilon_1^\alpha = \frac{\Gamma(N_1 \to \phi \ell_\alpha) - \Gamma(\bar{N}_1 \to \bar{\phi}\bar{\ell}_\alpha)}{\Gamma(N_1 \to \phi \ell) + \Gamma(\bar{N}_I \to \bar{\phi}\bar{\ell})} \qquad \text{(recall } N_1 = \bar{N}_1\text{)}$$

Very simple case: $I = 1$, $M_1 \ll M_{2,3}$



$\not{CP}$ and $\not{L}$

HamaguchiMurayamaYanagida
Davidson Ibarra

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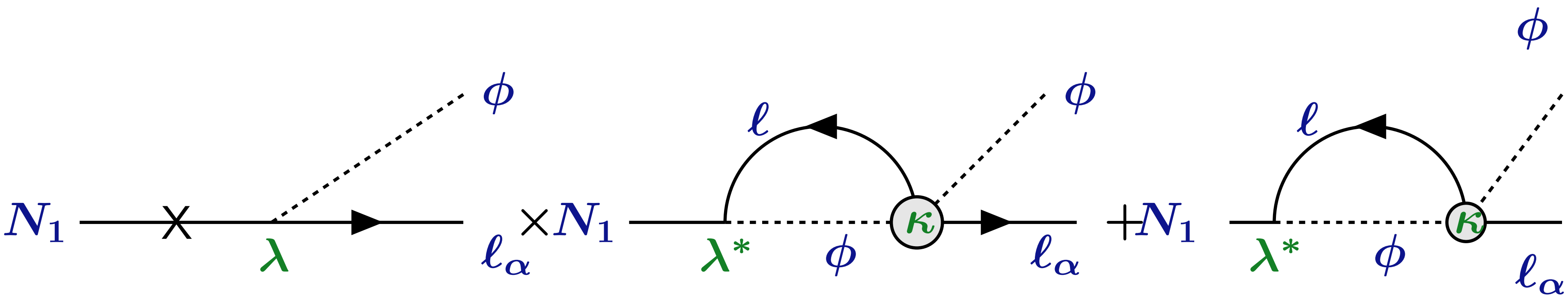
Very simple case: $I = 1$, $M_1 \ll M_{2,3}$, $[\kappa]_{\alpha\beta} \sim \frac{[m_\nu]_{\alpha\beta}}{v^2}$



$$\sum_\alpha \epsilon_1^\alpha < \frac{3}{16\pi}\frac{m_\nu^{max} M_1}{v^2} \qquad \sim 10^{-6} \ \frac{M_1}{10^9 \text{GeV}} \qquad \gtrsim 10^{-6}$$

so for $M_1 \ll M_{2,3}$, need $M_1 \gtrsim 10^9$ GeV to obtain sufficient ϵ
(but $\delta m_\phi^2 \sim m_\phi^2 \Rightarrow M_K < 10^8$ GeV ; need $M_I \sim M_J \Leftrightarrow$ resonantly enhance ϵ)

...and enter the wolf: thermal equilibrium

need $\not{T}\not{E}$ dynamics: if the $\not{L}$ interactions of N are in equilibrium, they will destroy any asymmetry in SM leptons generated by the $\not{C}\not{P}$.

How big a lepton asymmetry survives ?

1. First produce a population of Ns, via *e.g.* $(q\ell_\alpha \to N t_R)$ ($\alpha =$ lepton flavour).
   Suppose $\Gamma_{prod} \gg H$ (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

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

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

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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 ~~B+L~~ , $s \sim g_* n_\gamma$, $\epsilon_{\alpha\alpha}$ CP asym in decay)

$$\frac{n_B - n_{\bar{B}}}{s} \sim \frac{1}{3} \sum_\alpha \epsilon_{\alpha\alpha} \frac{n_N(T_\alpha)}{g_* n_\gamma} \sim 10^{-3}\, \epsilon \frac{H}{\Gamma} \qquad (\text{want } 10^{-10})$$

Washout : type-I seesaw Leptogenesis differs from "drift and decay"

(N are produced and disappear via Yukawa coupling)

In leptogenesis, people talk alot about "washout". Why?
(For GUT baryogenesis $X \to bb, b\ell$, just compute $\not{C}\not{P}$ ϵ?)

- a population of Ns is produced via its Yukawa coupling
  (eg $qt^c \to N\ell_\alpha$, $\phi\ell_\alpha \to \nu_R$).
- Population later disappears via same Yukawa coupling (eg. $N \to \phi\ell_\alpha$...)
- there is CP violation in production and disappearance...
  $\Rightarrow$ anti-asym. made with Ns exactly opposite to asym. made when Ns go away
  (In the case I calculated)
  $\Rightarrow$ thermal leptogenesis "works", because Yukawa interactions deplete the asym between production and disappearance of N population $\equiv$ **washout**.

  For instance: N interactions fast, washout effective = the asym made with Ns is destroyed.

  Or: N interactions slow, washout mild = the asym made with Ns must be included.

So differ from the GUT case, where produced X via gauge interactions.

α and β in this talk $\in \{e, \mu, \tau\}$: does lepton flavour matter ?

SM B+L violn eats B+L; why worry about flavour asymmetries?

α and β in this talk $\in \{e, \mu, \tau\}$: does lepton flavour matter ?

Suppose the lepton asymmetry produce in the decay of N_1. Suppose h_τ "in equilibrium", so τ leptons are $distinct$ propagation eigenstates from $o = e, \mu$.

Then the lepton asym produced in decays is the sum of $\epsilon^\tau + \epsilon^o$.

But the lepton asym that survives is $(\eta_\alpha \sim H/\Gamma(N \to \ell_\alpha \phi))$

$$\sim 10^{-3}(\epsilon^\tau \eta_\tau + \epsilon^o \eta_o) \neq 10^{-3}(\epsilon^\tau + \epsilon^o)(\eta_\tau + \eta_o)$$

because should estimate washout with incident propagation eigenstates τ and o

o is a lin combo of e and μ.

$\Rightarrow$ maybe yes, depends on your scenario

Can leptogenesis (in the type I seesaw) be tested?

Recall $+$ 18 parameters in the high-scale $\mathcal{L}$, 9 in light ν masses and mixing.
...? need to measure M_I, BRs of N_I?

1. to find a heavy singlet neutrino N?
   – νMSM: $N_{2,3}$ flux behind SPS beam dump? Bonivento etal 2013
   – gauged $B-L$: $Z' \to N\bar{N} \to 4\ell$ @ LHC Blanchet etal 2010
   (but generically, $M \sim$ TeV $\Rightarrow \lambda \ll 1 \Leftrightarrow$ limited collider production)

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   — find Majorana m_ν in $0\nu2\beta$ expts this is a prediction of the seesaw...

   Conversely, seesaw falsefied (?) if find Dirac m_ν (= no $0\nu2\beta$+ inverse hierachy in m_ν)

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3. reassuring if
   — find $\not{CP}$ in neutrino oscillations confirms there is $\not{CP}$ in leptons (required for leptogen)
4. ? measure T_{reheat} ? (CMB ? : amplitude, tensor/scalar. Or gravity waves?) Martin+Ringeval
   an upper bound on the scale M: different from δm^2_ϕ, solid for thermal N production BuchmullerDomckeKamadaSchmitz
5. SUSY at the LHC? lepton flavour violation (LFV), like $\mu \to e\gamma$, $\tau \to \mu\gamma$ ...?

$\Rightarrow$ only in special cases (eg νMSM)

...to do a credible calculation?

Two steps:

1. formulate equations (recall: Boltzmann Eqn in 1872. Planck constant in 1900)

2. solve/calculate/approximate/resum, etc

To obtain kinetic eqns?

variables: want to know n_N, $n_{B/3-L_\alpha}$

eqns, v1: operator for density matrix of U, $\hat{\rho}(t) = e^{iH_{SM}t}\hat{\rho}e^{-iH_{SM}t}$ GagnonShaposhnikov

Bodeker/Laine/etal

$$i\frac{d\hat{\rho}(t)}{dt} = [\hat{H}_{seesaw}, \hat{\rho}(t)] \quad , \quad \hat{H}_{seesaw} \supset \lambda\bar{\hat{\ell}}\hat{\phi}\hat{N} + M\hat{N}\hat{N}^c$$

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perturbation theory in λ ("all orders in SM")
SM particles in TE
small times ? $< \tau_U$?

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eqns ,v2: Schwinger-Dyson/Kadanoff-Baym/ EoM for 2pt fns in CTP etal+ Kartavtsev
(usually) suppose equilibrium for SM distributions Beneke etal
pert theory in λ ("all orders in SM")
times $< 1/T$?

v1,v2 same (?) Sometimes Boltzmann Eqns work! (not when alternate paths with same weight)

...to do a credible calculation?

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2. solve/calculate/approximate/resum, etc

   ...need to include SM interactions...resummations even at LO :(

Anisimov,BesakBodeker

Summary

Generic recipe for a Universe where 6 protons live happily ever after with every 10^{10} photons (and protons don't decay):
Take a Universe containing the SM. Add:

heavy singlet neutrinos
$\not{C}\not{P}$ **and** $\not{L}$ **interactions**

Heat.
Cool, when sufficient singlets are present.
They will produce a lepton asymmetry, and the SM will transform it to a baryon asymmetry. (Some adjustment of parameters may be required).

Interesting calculations because

1. some scenarios are testable

2. can (probably)perturb in λ: tractable problem at high density, short times ? (before EWPT, to use SM $\not{B}+\not{L}$)