Of Cookbooks and Fairy Tales:

How neutrinos could make

the Universe we see

Sacha Davidson, IPN de Lyon, France
One number: \[ \left. \frac{nB-n\bar{B}}{n\gamma} \right|_0 \approx 6 \times 10^{-10} \]

Three ingredients: \( B, \ CP, \ TE \)

...many recipes...

\[ \textbf{Leptogenesis} \equiv \text{non-equil. generation of } Y_L \]

“sphalerons” redistribute to \( Y_B \)

\[ \textbf{Sacha Davidson} \]

IPN de Lyon/CNRS, France

1. a vanilla scenario: type I seesaw
   \( \sim \) estimates
   \textit{particularities} : “washout”, and “flavour”

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

3. can one make reliable predictions?
   ...parallel sessions:Eijima, Kartavtsev,
A baryon excess today:

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To be produced after inflation (dilutes previous asymms)
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Ingredients to prepare in the early U (old russian recipe)

1. **B**: required to evolve from \( B = 0 \) state to \( B \neq 0 \) state

2. **\( CP \)**: particles and anti-part must behave differently (to avoid making equal asym and anti-asym)

3. **TE**: no asyms in thermal equil. for unconserved Q #s
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Present in SM, but hard to combine to give big enough asym \( Y_B \)

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

One observation to fit, many new parameters...

\( \Rightarrow \) prefer BSM motivated by other data \( \Leftrightarrow m_\nu \Leftrightarrow \text{seesaw}! \) (uses non-pert. SM B±I)
The (type I) Seesaw

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

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

$M_I$ unknown ($\phi v = \langle \phi^0 \rangle$), and Majorana ($L$). CP in complex $\lambda_{\alpha J}$.
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- at low scale, for $M \gg m_D = \lambda v$, light $\nu$ mass matrix

$$\nu_L \xrightarrow{v \lambda x^{\alpha A}} M_A \xrightarrow{v \lambda x^{\beta A}} \nu_L$$

$\nu L \alpha$ $\nu L \beta$

$N_A$

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

for $\lambda \sim h_t$, $M \sim 10^{15} \text{ GeV}$

$\lambda \sim 10^{-4}$, $M \sim 10^7 \text{ GeV}$

$\sim .05 \text{ eV}$

“natural” $m_\nu \ll m_f$: $m_\nu \propto \lambda^2$, and $M > v$ allowed.
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$M_I$ unknown ($\phi v = \langle \phi^0 \rangle$), and $L \cdot \mathbb{CP}$ in $\lambda_{\alpha J}$.

- at low scale, Higgs mass contribution

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

for $M \gtrsim 10^7$ GeV $> v^2$

(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 $\geq 2$ loop? ...

(NB, in this talk, $\phi = $ Higgs, $H = $ Hubble)
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 $L$ masses and $\mathbb{CP}$ interactions) to the Universe.

The adventure begins after inflationary expansion of the Universe:
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1. Assuming its hot enough, a population of $N$s appear, because they like the heat.

2. As the temperature drops below $M$, the $N$ population decays away.
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1. Assuming its hot enough, a population of $N$s appear, because they like the heat.
2. As the temperature drops below $M$, the $N$ population decays away.
3. In the CP and $L$ 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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1. Assuming its hot enough, a population of $N$s appear, because they like the heat.

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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 were 6 extra baryons (wrt anti-baryons).
\( CP \) and \( L \)

\( CP, L : N_1 \) interactions generate an excess of leptons \( \ell_\alpha \) with respect to anti-leptons \( \bar{\ell}_\alpha \) (\( CP \) from complex coupling \( \times \) (tree \( \times \) on-shell loop)). For instance:

\[
\epsilon^\alpha_I = \frac{\Gamma(N_I \rightarrow \phi \ell_\alpha) - \Gamma(\bar{N}_I \rightarrow \bar{\phi} \bar{\ell}_\alpha)}{\Gamma(N_I \rightarrow \phi \ell) + \Gamma(\bar{N}_I \rightarrow \bar{\phi} \bar{\ell})} \quad \text{(recall } N_I = \bar{N}_I\text{)}
\]

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

finite temp: Beneke et al. 10
\( \mathcal{CP} \) and \( L \): \( N_1 \) interactions generate an excess of leptons \( \ell_\alpha \) with respect to anti-leptons \( \bar{\ell}_\alpha \) (\( \mathcal{CP} \) from tree \( \times \) loop interference). For instance:

\[
\epsilon^\alpha_1 = \frac{\Gamma(N_1 \to \phi \ell_\alpha) - \Gamma(\bar{N}_1 \to \bar{\phi} \bar{\ell}_\alpha)}{\Gamma(N_1 \to \phi \ell) + \Gamma(\bar{N}_1 \to \bar{\phi} \bar{\ell})}
\]

(recall \( N_1 = \bar{N}_1 \))

Very simple case: \( I = 1 \), \( M_1 \ll M_{2,3} \)
$\mathcal{C}\mathcal{P}$ and $\mathcal{L}$

$\mathcal{C}\mathcal{P}, \mathcal{L}$: $N_1$ interactions generate an excess of leptons $\ell_\alpha$ with respect to anti-leptons $\bar{\ell}_\alpha$. For instance:

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

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

so for $M_1 \ll M_{2,3}$, need $M_1 \gtrsim 10^9$ GeV to obtain sufficient $\epsilon$ (but $\delta m_\phi^2 \sim m_\phi^2 \Rightarrow M_K < 10^8$ GeV; need $M_I \sim M_J \Leftrightarrow$ resonantly enhance $\epsilon$)
...and enter the wolf: thermal equilibrium

need $\text{TE}$ dynamics: if the $L$ interactions of $N$ are in equilibrium, they will destroy any asymmetry in SM leptons generated by the $\text{CP}$.
How big a lepton asymmetry survives?

1. First produce a population of $N$s, via e.g. $(q\ell_\alpha \rightarrow N t_R)$ ($\alpha =$ lepton flavour).
   Suppose $\Gamma_{\text{prod}} \gg H$ (timescale for production interactions is shorter than the age of the U)
   $\Rightarrow$ produce the (maximal) thermal population $n_N \approx n_\gamma$ at $T \gtrsim M_1$, and
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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 $N$s.
   The lepton asymm in flavour $\alpha$ (produced from $N$ decay) can survive after Inverse Decays from flavour $\alpha$ turn off when $\Gamma_{ID}(\ell_\alpha \phi \rightarrow N) < H$:
   $$\Gamma_{ID}(\ell_\alpha \phi \rightarrow N) \simeq \Gamma(N \rightarrow \ell_\alpha \phi)e^{-M_1/T} < H$$
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   $$\Gamma_{ID}(\ell_\alpha \phi \rightarrow N) \simeq \Gamma(N \rightarrow \ell_\alpha \phi)e^{-M_1/T} < H$$

   At temperature $T_\alpha$ when Inverse Decays from flavour $\alpha$ turn off,

   $$\frac{n_N(T_\alpha)}{n_\gamma} \simeq e^{-M_1/T_\alpha} \simeq \frac{H}{\Gamma(N \rightarrow \ell_\alpha \phi)}$$

   can calculate this.

   so (1/3 is from SM $B + L$, $s \sim g_s n_\gamma$, $\epsilon_{\alpha \alpha}$ CP asym in decay)

   $$\frac{n_B - n_{\bar{B}}}{s} \sim \frac{1}{3} \sum_\alpha \epsilon_{\alpha \alpha} \frac{n_N(T_\alpha)}{g_s n_\gamma} \sim 10^{-3} \frac{H}{\Gamma}$$

   (want $10^{-10}$).
In leptogenesis, people talk a lot about “washout”. Why? (For GUT baryogenesis $X \to bb, b\ell$, just compute $\mathcal{CP} \epsilon$?)

- a population of $N$s is produced via its Yukawa coupling (eg $q^c t \to N\ell_\alpha$, $\phi\ell_\alpha \to \nu_R$).

- 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 $N$s exactly opposite to asym. made when $N$s 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 $N$s is destroyed.

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

So differ from the GUT case, where produced $X$ via gauge interactions.
\(\alpha\) and \(\beta\) in this talk \(\in \{e, \mu, \tau\}\): does lepton flavour matter?

SM \(B+L\) violating eats \(B+L\); why worry about flavour asymmetries?
\( \alpha \) and \( \beta \) in this talk \( \in \{e, \mu, \tau\} \): does lepton flavour matter?

Suppose the lepton asymmetry produce in the decay of \( N_1 \). Suppose \( h_\tau \) “in equilibrium”, so \( \tau \) 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 \((\eta_\alpha \sim H/\Gamma(N \rightarrow \ell_\alpha \phi))\)

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

because should estimate washout with incident propagation eigenstates \( \tau \) and \( o \)

\( o \) is a lin combo of \( e \) and \( \mu \).

\[ \Rightarrow \] 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 \( \nu \) masses and mixing. ...? need to measure \( M_I \), BRs of \( N_I \)?

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

Bonivento et al. 2013
Blanchet et al. 2010
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2. supported if
   - find Majorana $m_\nu$ in $0\nu2\beta$ expts this is a prediction of the seesaw...

Conversely, seesaw falsefied (?) if find Dirac $m_\nu$ (= no $0\nu2\beta$+ inverse hierarchy in $m_\nu$)
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3. reassuring if
   - find $\mathcal{CP}$ in neutrino oscillations confirms there is $\mathcal{CP}$ in leptons (required for leptogen)

4. ? measure $T_{\text{reheat}}$? (CMB ?: amplitude, tensor/scalar. Or gravity waves?)
   - an upper bound on the scale $M$: different from $\delta m_\phi^2$, solid for thermal $N$ production

5. SUSY at the LHC? lepton flavour violation (LFV), like $\mu \rightarrow e\gamma$, $\tau \rightarrow \mu\gamma$ ...

$\Rightarrow$ only in special cases (eg $\nu$MSM)
...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 $U$, $\hat{\rho}(t) = e^{iH_SMt} \hat{\rho} e^{-iH_SMt}$

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

$$\hat{\rho}(t) = \hat{\rho}(t_0) - i \int dt'[\hat{H}_{\text{seesaw}}(t'), \hat{\rho}] - \int dt' \int t' dt'' [\hat{H}_{\text{seesaw}}(t') [\hat{H}_{\text{seesaw}}(t''), \hat{\rho}]] + ...$$

perturbation theory in $\lambda$ ("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 (usually) suppose equilibrium for SM distributions

pert theory in $\lambda$ ("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?

Two steps:

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

2. solve/calculate/approximate/resum, etc

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

**$\mathcal{CP}$ and $L$ 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 $\lambda$: tractable problem at high density, short times? (before EWPT, to use SM $B+L$)