Of Cookbooks and Fairy Tales:

How neutrinos could make the Universe we see

Sacha Davidson, IPN de Lyon, France

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   $\approx H \approx$ baryons

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$\Rightarrow$ Question : where did that excess come from ?

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   - (only theory explaining coherent temperature fluctuations in microwave background that arrive from causally disconnected regions today...)
   - "60 e-folds" inflation $\equiv V_U \rightarrow> 10^{\mathbf{90}} V_U$

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3. created/generated/cooked after inflation...

One number : $\left.\frac{n_B - n_{\bar{B}}}{n_\gamma}\right|_{\mathbf{0}} \simeq 6 \times 10^{-\mathbf{10}}$

...many recipes...

$$\textit{Leptogenesis} \equiv \begin{array}{l} \textit{non-equil. generation of } \boldsymbol{Y_L} \\ \textit{“sphalerons” redistribute to } \boldsymbol{Y_B} \end{array}$$

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1. preliminaries
   3 ingredients
   fast $\cancel{\mathrm{B+L}}$ at $T > m_W$ in the Standard Model
   observe m_ν, but no p decay $\Rightarrow$ leptogenesis ?
2. the matter excess in the type I seesaw (**heavy**, hierarchical N_R)
   the fairy tale
   $\sim$ estimates
   can it be tested ? or is it a physicists fairytale ? There is a wolf...
3. νMSM (type 1 seesaw with $m_N < m_W$)
   is testable(?)

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to be produced after inflation(dilutes previous asyms)

Three ingredients to prepare in the early U (old russian recipe)

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   From end inflation → BBN, Universe is an expanding, cooling thermal bath, so non-equilibrium from :
   - slow interactions : $\tau_{int} \gg \tau_U$ = age of Universe ($\Gamma_{int} \ll H$)
   - phase transitions :

ingredient 1 : Does the SM conserve B ?

B, L are global symmetries of the SM Lagrangian (q, ℓ doublets, e, u, d singlets)

$$\mathcal{L}_{SM} \supset \overline{q} \not{D} q \ , \ \overline{\ell} \not{D} \ell \quad , \quad \overline{\ell} H e \quad , \quad \overline{q} \widetilde{H} u \quad , \quad \overline{q} H d$$

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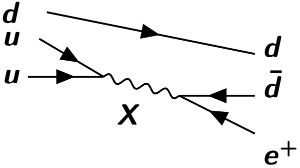
Consider adding "X" with $\not{B}$ interactions :



$$\Gamma(p \to e^+ \pi) \sim \frac{\alpha^2 m_p^5}{m_X^4} \sim \left(\frac{10^{16} \text{ GeV}}{m_X} \right)^4 \times 10^{33} \text{ yrs}$$

(**tension** with inflation scale, **issues** about presence of equilibrium, using field theory...)

ingredient 1 : But the SM *does not* conserve $B + L$...

in QFT, there is the axial anomaly...
...anomalously, the fermion current associated to a classical symmetry is not conserved.

see Polyakov,
"Gauge Fields + Strings,"
6.3=qualitative effects of instantons

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$$\sum_{\frac{SU(2)}{singlets}} \partial^\mu(\overline{\psi}\gamma_\mu\psi) + \partial^\mu(\overline{\ell}\gamma_\mu\ell) + \partial^\mu(\overline{q}^\alpha\gamma_\mu q_\alpha) \propto \frac{1}{64\pi^2} W^A_{\mu\nu}\widetilde{W}^{\mu\nu A}.$$

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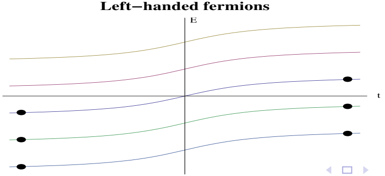

thanks to V Rubakov

SM B+L violation : rates

't Hooft
Kuzmin Rubakov+
Shaposhnikov

At $T = 0$ is tunneling process (from winding # to next, "instanton") :
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$\star\star\star$ SM $\not{\rm B}+\not{\rm L}$ is $\Delta B = \Delta L = 3$ $(= N_f)$. No proton decay ! $\star\star\star$

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One observation to fit, many new parameters...

$\Rightarrow$ *prefer BSM motivated by other data* $\Leftrightarrow m_\nu \Leftrightarrow$ *seesaw !*

(uses non-pert. SM $\cancel{B+L}$)

The type I seesaw

Minkowski, Yanagida
Gell-Mann Ramond Slansky

- add 3 singlet N to the SM in charged lepton and N mass bases, at 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 ($\not{L}$). $\not{CP}$ in $\boldsymbol{\lambda}_{\alpha J} \in \boldsymbol{C}$.

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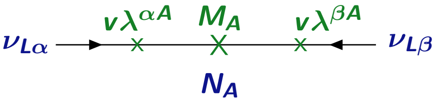
- at low scale, for $M \gg m_D = \lambda v$, light ν mass matrix



9 parameters :
m_1, m_2, m_3
6 in U_{MNS}

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

for $\lambda \sim h_t$, $M \sim 10^{15}$ GeV
$\lambda \sim 10^{-7}$, $M \sim 10$ GeV

$$\sim .05 \text{ eV}$$

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

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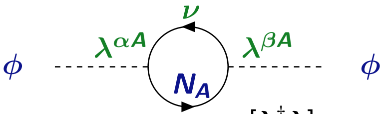
- at low scale, Higgs mass contribution



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

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

(? adding particles to cancel 1 loop...but higher loop ? Need symmetry to cancel $\geq$ 2 loop ?)

$\Rightarrow$ do seesaw with $M_I \lesssim 10^8$ GeV ?

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

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

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3 In the $\not{CP}$ and $\not{L}$ interactions of the N, an asymmetry in SM leptons is created.

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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).

Estimate something : $\cancel{\mathrm{TE}}$ + dynamics Suppose $M_1 \ll M_{2,3}$, $T_{reheat} > M_1 \sim 10^9\,\mathrm{GeV}$

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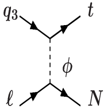
1 produce a population of N_1s, via *e.g.* $(q\ell_\alpha \to Nt_R)$
Get thermal density $n_N \simeq n_\gamma$ if $M_1 \lesssim T$, and $\tau_{prod} < \tau_U$:



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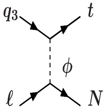

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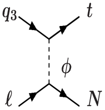

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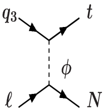
Suppose satisfied...

Later, Lepton asym is produced in N decay if there is $\cancel{CP}$, and it is "out of equilibrium". Naive $\cancel{TE}$ condition, $\Gamma_{decay} < H(T = M)$:

$$\Gamma_{decay} = \frac{[\lambda\lambda^\dagger]_{11} M_1}{8\pi} < \left. \frac{10\,T^2}{m_{pl}} \right|_{T=M_1}$$

Ack !

Estimate something : $\not{T}\not{E}$ + dynamics Suppose $M_1 \ll M_{2,3}$, $T_{reheat} > M_1 \sim 10^9$GeV



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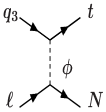

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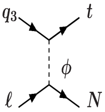

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so (1/3 is from SM ~~B+L~~ , $s \sim g_* n_\gamma$, ϵ_α is lepton asym in decay)

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

Estimate ϵ, the CP and L asymmetry in decays

Recall (in **S**-matrix) $CP : \langle \phi\ell | \boldsymbol{S} | N \rangle \to \langle \overline{\phi\ell} | \boldsymbol{S} | \overline{N} \rangle = \langle \overline{\phi\ell} | \boldsymbol{S} | N \rangle$, ($\overline{\eta}$ =anti-η)

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finite temp :Beneke etal 10

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

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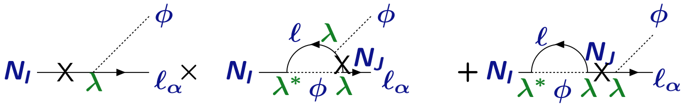

Just try to calculate ϵ_1 ?

- no asym at tree
- asym at tree $\times$ loop, *if* $\not{CP}$ from complex cpling *and* on-shell particles in the loop (divergences cancel in diff, need Im part of Feynman param integrtn)

$\not{C}\not{P}$, complex couplings, loops unitarity and all that...(estimate ϵ, no loop caln)

Kolb+Wolfram, NPB '80, Appendix

1 the S-matrix $\boldsymbol{S} \equiv \mathbf{1} + i\boldsymbol{T}$ is CPT invariant

$$\langle\overline{\phi\ell}|\boldsymbol{S}|N\rangle = \langle N|\boldsymbol{S}|\phi\ell\rangle \quad (= \langle\phi\ell|\boldsymbol{S}^\dagger|N\rangle^*)$$

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2 We are interested in a $\not{C}\not{P}$ asymmetry :

$$\epsilon \propto \int d\Pi\Big(|\langle\phi\ell|\boldsymbol{T}|N\rangle|^2 - \langle\overline{\phi\ell}|\boldsymbol{T}|N\rangle|^2\Big)$$

SO (this formula exact, if I kept 2s and sums)

$$\epsilon \propto \boldsymbol{Im}\Big\{\langle\phi\ell|\boldsymbol{T}^\dagger|N\rangle\langle N|\boldsymbol{T}\boldsymbol{T}^\dagger|\phi\ell\rangle\Big\}$$

$\Rightarrow$ need complex cplings, and on-shell particles in a loop

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Consider simple case : $M_1 \ll M_{2,3}$. Suppose lepton asym generated in $\not{CP}$, $\not{L}$ decays of N_1 :

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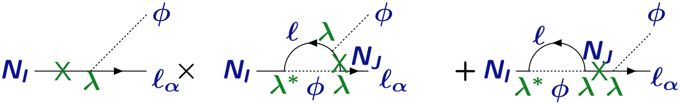
(NB, no intermediate N_1 because cplg combo real)



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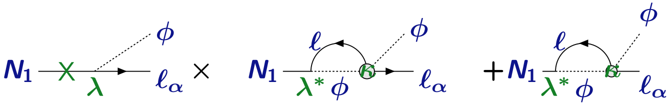

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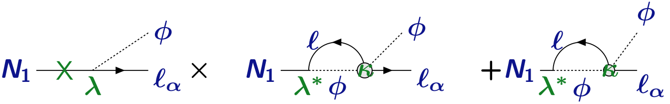

Recall

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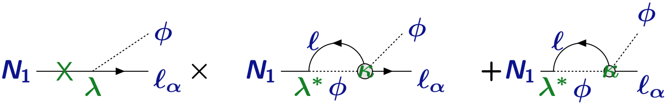

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because $\quad \langle \phi\ell | \boldsymbol{T} | N \rangle = \mathcal{M}(N \to \phi\ell)(2\pi)^4 \delta^4(\sum p_i - \sum p_f)$

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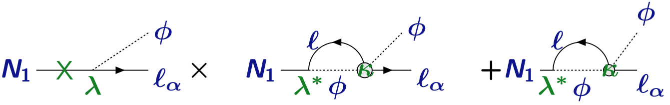

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$$\epsilon_1 < \frac{3}{8\pi}\frac{m_\nu^{max} M_1}{v^2} \qquad \sim 10^{-6} \frac{M_1}{10^9\text{GeV}} \qquad \gtrsim 10^{-6}$$

so for $M_1 \ll M_{2,3}$, need $M_1 \gtrsim 10^9$ GeV to obtain sufficient ϵ

Ouff : summary about simplest model and going beyond

1. type 1 seesaw model with hierarchical N_I :
   suppose scattering in thermal bath produces abundance of $N_1 \sim T^3$, N_1decays produces lepton asym ; asym survives after Γ_{ID} goes $\cancel{\mathrm{TE}}$ sphalerons transform to baryon asym.

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   credibility enhanced if measure Majorana m_ν $(0\nu 2\beta)$
   and if measure $\not{C}\not{P}$ in the lepton sector
   and if measure $T_{reheat} > 10^9$ GeV

grav waves ? BuchmullerDomcke etal
CMB ? Martin etal

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$\Rightarrow$ How to do leptogenesis with $M_K < 10^7$ GeV ?

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2. But at lower T, age of Universe is longer, is there sufficient out-of-equilibrium ?
   1) want to reproduce neutrino masses

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   2) need to decay before Electroweak PT (to profit from sphalerons)...
   ...more restrictive : need $\cancel{\mathrm{TE}}$. Only keep the asym produced by Ns who decay after inverse decays $\Gamma_{ID}(\phi\ell \to N)$ go out of equilibrium (must happen before EWPT) :

$$\Gamma_{ID} \sim e^{-M/T}\Gamma(N \to \phi\ell) < H \quad \Rightarrow \quad M \gtrsim 10\, T_c$$

Fairy tale works for degen N_I for $M_I \gtrsim$ TeV

(but are $M_I \sim$ TeV any more detectable than $M_I \sim 10^{\mathbf{9}}$ GeV ?)

νMSM : type 1 seesaw below 100 GeV gives BAU and DM

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...

ingredients : SM +

$N_{2,3}$: 100 MeV $\lesssim M_{2,3} \lesssim$ 10 GeV, $\Delta M \lesssim \begin{cases} 10^{-6}\ \mathrm{eV} & Y_B, \Omega_{DM} \\ \mathrm{keV} & Y_B, NOT\ \Omega_{DM} \end{cases}$

Yukawas $\ni$ give 2 light SM neutrinos via seesaw mechanism

N_1 : $M_1 \sim$ keV. WDM candidate.

feebly coupled (difficult to produce, negligeable contribution $m_{\nu,SM}$)

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Population of $N_{2,3}$ produced via Yukawas before EPT
Produce $\Delta L \to Y_B$ via oscillations of $N_{2,3}, \nu_{SM}$ before EPT (+ backreactn !)
Produce $\Delta L \gtrsim 10^{-5}$ via oscillations and decay of $N_{2,3}$ after EPT
Allows to produce sufficient distribution of N_1 via oscillations around QCD PT in SM ν.

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tests :

N_1 as DM : X-rays from DM decay, WDM bounds (depend on momentum distribution)
$N_{2,3}$: beam dump, SHIP

How does asym generation work ? (very simplified !)

1 at $T \lesssim TeV$ (recall $\lambda \lesssim 10^{-7}$) , produce N_2, N_3 via Yukawa interaction $\lambda \overline{N} \ell \cdot \phi$

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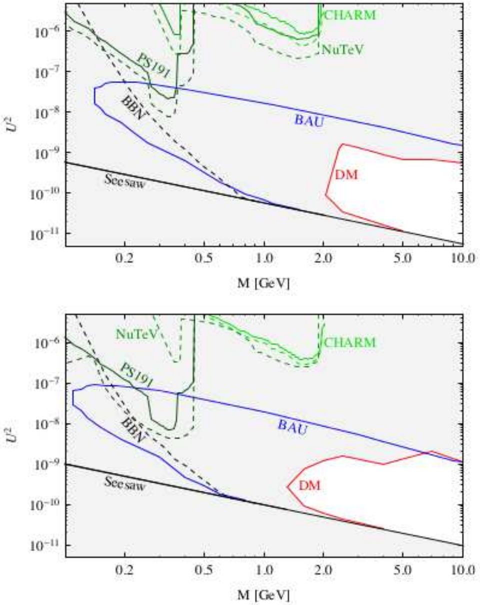
2 N_2, N_3 oscillate (almost degenerate)
3 back to ν_L via λ
at $\tau_U \sim \tau_{osc}$, 1,2,3 are *coherent*, so CPV from λ-ΔM^2-λ gives flavour asyms in $\nu_{L\alpha}$ (to small)
lepton number in $\ell_L + N_R$ is conserved (actually, $L_{SM}+$ helicity of N_I)
from $\tau_{osc} \to \tau_{EWPT}$, asyms in $\nu_{L\alpha}$ seed asyms in $N \longrightarrow$ asyms in $\nu_{L\alpha}$ (enough asym)
...works also in detailed calculations with all available technology...
(eg also include lepton number violating interactions)

Teresi Hambye
Eijima + Shaposhnikov
Ghiglieri+ Laine



$$U^2 = \mathrm{Tr}[\lambda M^{-2} \lambda^\dagger]$$

Summary

The visible Universe today is made of baryonic matter, and negligeable anti-matter. This excess should be produced during the evolution of the Universe — after inflation, (and before BigBangNucleosynthesis).

The three required ingredients are B number violn, C+CP violn, and a departure from thermal equilibrium. All are present in the SM of particle phys and cosmo...but noone has figured out how to combine them to generate the observed asym. Therefore the matter excess is taken as *evidence for Beyond-theStandard-Model* Physics.

Leptogenesis is a class of recipes, that use majorana neutrino mass models to generate the matter excess. The "new physics" in the lepton sector should generate a lepton asymmetry in the early Universe (before the Electroweak Phase Transition), and the non-perturbative SM B+L violn will partially reprocess it to a baryon excess.

⋆ efficient, to use the BSM for m_ν to generate the Baryon Asym.

⋆ using SM B+L violn ($\Delta B = \Delta L = 3$) avoids proton lifetime bound

⋆ *it works* ...rather well, for a wide range of parameters