Leptogenesis

a class of recipes, that use (majorana) neutrino mass models to generate the matter excess

- what matter excess ?
- required ingredients ?
- a simple seesaw model
- how it works...

Preamble

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3. quantify as ($s_0 \simeq 7 n_{\gamma,0}$)

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PLANCK

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

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   X no ! After birth of U, there was "inflation"
   - (only theory explaining coherent temperature fluctuations in microwave background that arrive from causally disconnected regions today...)
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3. created/generated/cooked after inflation...

Three ingredients to prepare in the early U (useful for organising caln)

Sakharov

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   Present in the SM quarks, observed in Kaons and Bs, searched for in leptons (...T2K,future expts)
3. out-of-thermal-equilibrium ...equilibrium = static. "generation" = dynamical process
   No asym.s in un-conserved quantum #s in equilibrium
   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 : the SM *does not* conserve $B + L$

$B + L$ is anomalous. Formally, for one generation(α colour) :

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

where integrating the RHS over space-time counts "winding number" of the SU(2) gauge field configuration.
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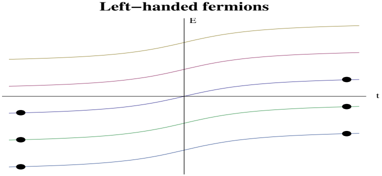

thanks to V Rubakov

SM B+L violation : rates

't Hooft
Kuzmin Rubakov+
Shaposhnikov

At $T = 0$ is tunneling process (from winding # to next, "instanton") : $\Gamma \propto e^{-8\pi/g^2}$

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

$\Rightarrow$ fast SM $\not{B+L}$ at $T > m_W$

$\Gamma_{\not{B+L}} > H$ for $m_W < T < 10^{12}$ GeV

SM $\not{B+L}$ called "sphalerons"
$\Rightarrow$ if produce a lepton asym, "sphalerons" partially transform to a baryon asym. ! !
⋆⋆⋆ SM $\not{B+L}$ is $\Delta B = \Delta L = 3$ $(= N_f)$. No proton decay ! ⋆⋆⋆

Summary of preliminaries : A Baryon excess today :

• Want to make a baryon excess $\equiv Y_B$ after inflation, that corresponds today to ~ 1 baryon per 10^{10} γs.

• Three required ingredients : $\not{B}$, $\not{CP}$, $\not{TE}$.
Present in SM, but hard to combine to give big enough asym Y_B

Cold EW baryogen ? ? Tranberg et al ...

⇒ evidence for physics Beyond the Standard Model (BSM)

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⇒ evidence for physics Beyond the Standard Model (BSM)

One observation to fit, many new parameters...

⇒ prefer BSM motivated by other data ⇔ m_ν ⇔ seesaw !
(uses non-pert. SM $\not{B+L}$)

Focus here on leptogenesis in seesaw model with $M_N \gtrsim 10^9$ GeV

Minkowski, Yanagida
Gell-Mann Ramond Slansky

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

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

add 18 parameters :
M_1, M_2, M_3
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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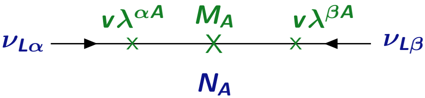
- at low scale, for $M \gg m_D = \lambda v$, light ν mass matrix



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 $\sim .05$ eV

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

The type I seesaw

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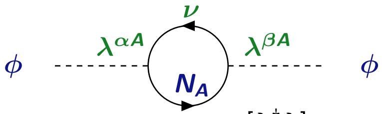
- at low scale, Higgs mass contribution



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

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 ≥ 2 loop ?)

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

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

Leptogenesis in the type 1 seesaw : usually a Fairy Tale

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Buchmuller et al
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Once upon a time, a Universe was born.

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The adventure begins after inflationary expansion of the Universe :

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

2 As the temperature drops below M, the N population decays away.

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

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If this asymmetry can escape the big bad wolf of thermal equilibrium...

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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 : $\not{T}\not{E}$ + dynamics

Suppose $M_1 \ll M_{2,3}$, $T_{reheat} > M_1 \sim 10^9$GeV

Recipe : calculate suppression factor for each Sakharov condition, multiply together to get Y_B :

$$\frac{n_B - n_{\bar{B}}}{s} \sim \frac{1}{3g_*}\epsilon_{L,CP}\eta_{TE} \sim 10^{-3}\epsilon\eta \qquad (\text{want } 10^{-10})$$

$s \sim g_* n_\gamma$, $\epsilon =$ lepton asym in decay, $\eta \sim \not{T}\not{E}$ process

No Boltzmann Eqns because

1.(time...)

2. Boltzmann lived before Planck : BE in the early U are a classical approx at $\rho \gg$ nucleus, $E \gg$ colliders...should start from QFT and derive them.

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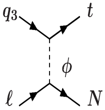

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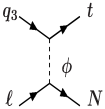

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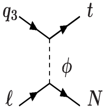

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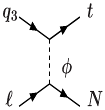

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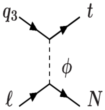

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so (1/3 is from SM B$\not{+}$L , $s \sim g_* n_\gamma$, ϵ_α is lepton asym in decay)

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

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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In leptogenesis, need $\not{CP}$, $\not{L}$ interactions of N_I...for instance :

finite temp :Beneke etal 10

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

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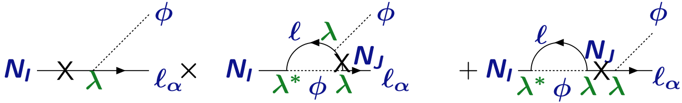

Just try to calculate ϵ_1 ?

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

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

Kolb+Wolfram, NPB '80, Appendix

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

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

and unitary : $\boldsymbol{S}\boldsymbol{S}^\dagger = 1 = (1 + i\boldsymbol{T})(1 - i\boldsymbol{T}^\dagger)$

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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 ; $\int d\Pi$ = phase space)

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

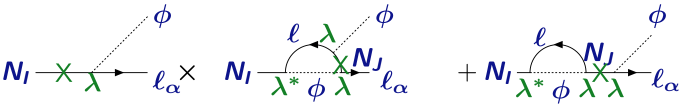
$\Rightarrow$ need complex cplings, and on-shell particles in a loop

Estimating ϵ for hierarchical N_I

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

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

(NB, no intermediate N_1 because cplg combo real)



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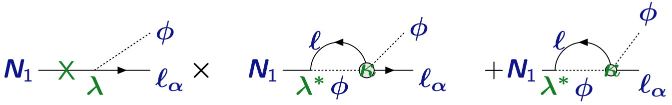

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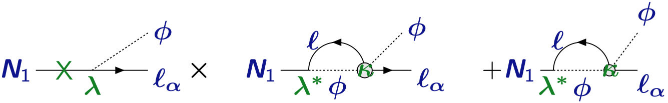

Recall

$$\Gamma \epsilon \sim \boldsymbol{Im}\left\{ \langle \overline{\phi\ell} | \boldsymbol{T} | N \rangle^* \langle N | \boldsymbol{T} | \overline{\phi\ell} \rangle \langle \overline{\phi\ell} | \boldsymbol{T}^\dagger | \phi\ell \rangle \right\}$$

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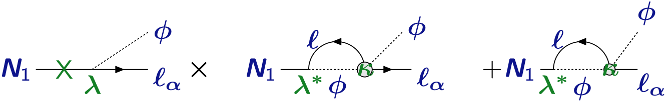

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$$\epsilon_1 \sim M \frac{\textbf{\textit{Im}}\{\lambda \lambda \kappa^*\}}{8\pi |\lambda|^2}$$

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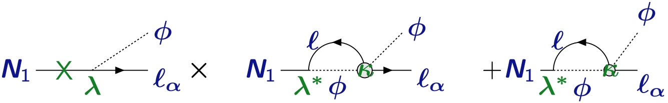

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$$\Gamma\epsilon \propto \int d\Pi\, \boldsymbol{Im}\left\{\mathcal{M}^*(N \to \overline{\phi\ell})\mathcal{M}(N \to \phi\ell)\mathcal{M}(\overline{\phi\ell} \to \phi\ell)\right\}$$

$$\epsilon_1 \sim M\frac{\boldsymbol{Im}\{\lambda\lambda\kappa^*\}}{8\pi|\lambda|^2} < \frac{3}{8\pi}\frac{m_\nu^{max}M_1}{v^2} \sim 10^{-6}\ \frac{M_1}{10^9\mathrm{GeV}} \gtrsim 10^{-6}$$

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

Maybe want $M_K < 10^9$ GeV? Leptogenesis with lighter N_I...

1. $M_I \sim M_J \Leftrightarrow$ resonantly enhance ϵ ... up to $\epsilon \lesssim 1$.
2. at lower T, age of Universe is longer, takes more care to get out-of-equilibrium...
3. need to generate L asym before Electroweak PT (to profit from sphalerons)...

$\Rightarrow$ leptogenesis via N_I decay/scattering works for degen N_I down to $M_I \sim$ TeV

For even lighter M_I, can make asym by coherent oscillations and scatterings of N_I...

Summary

Leptogenesis is a class of recipes, that use (majorana) neutrino mass models to generate the matter excess. The model generates a lepton asymmetry (before the Electroweak Phase Transition), and the non-perturbative SM B+L violn reprocesses 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