Beyond 3 massive active ν

Beyond 3 (slightly) massive active ν

How : add new light particles(need models) $M \lesssim 10$ GeV
add new heavy particles (can do EFT)$M \gg 10$ GeV

Why : explain some data (osc. anomalies (light ν_S ?), leptogen...)
address a theory problem (majorana operator non-renorm., small masses, large angles...)
predict new observables : LeptonFlavour Violation — distinguish models

Outline :

1. some seesaw models (make majorana masses)

(renormalisable,minimal, can be natural, leptogenesis)

2. leptogenesis

(heavy singlets, νMSM)

(3. EFT + (Charged)Lepton Flavour Violation)

Things I am unlikely to talk about...

1. not light steriles (I am not expert)
   various oscillation anomalies can be fit by sterile, $\Delta m^2 \gtrsim$ eV^2 fits several, but global fit not improved ?
2. not models/symmetries that explain small couplings, large angles...(I am not a model builder)
3. probably not NonStandardInteractions = NSI (offend my EFT preconceptions)
   dim 8 operators with $\Lambda_{NP} \sim$ few TeV, gives ν-LFV, but no dim6 Charged LFV.
4. Lepton Universality Violation
   exists in SM...

Two simple ways to add m_ν to the SM

1 add $\{\nu_R\}$ + Yukawa couplings : $\mathcal{L}_{SM} \to \mathcal{L}_{SM} + \lambda \bar{\ell} \tilde{H} \nu_R + h.c.$
— renormalisable, L-conserving-$m_\nu \equiv$ "Dirac"
— $\mathcal{A}_{LFV} \propto \frac{m_\nu^2}{m_W^2}$, mutiplicative GIM suppression

2. add "Weinberg operator" : $\mathcal{L}_{SM} \to \mathcal{L}_{SM} + \frac{\ell H \ell H}{\Lambda} + h.c.$
— non-renormalisable (dim 5), $\not{L}$ -$m_\nu \equiv$ "Majorana"
— $\mathcal{A}_{LFV}$ diverges...(need maaaaany counterterms ; not predictive)

3. could add non-renormalisable but L-conserving, or higher-dim $\not{L}$.

Since "Dirac" masses are boring (suppressed LFV), lets consider case of heavy NP in the lepton sector.

Assume heavy NP in lepton sector ; to calculate something ? :

1 replace non-renorm operator by a renorm. model

- predict all observables
- identify correlations $\leftrightarrow$ distinguish models ?

$+ \approx$ scientific method = construct hypothesis then test

$-$ much pursued : invent models faster than exclude

2 *add* the counterterms.

$\Rightarrow$ add dim 6 LFV operators to $\mathcal{L}_{SM}$, with arbitrary coefficients $\Leftarrow$ EFT

(can subtract divs, impose exptal constraints on coeffs)

$+$ separate known (SM + data), from not (BSM)

$-$ less predictive ? What to do ?

$\Rightarrow$ measure/constain coefficients, translate to Λ_{NP}, *then* try to build model indicated by the data

(parenthesis about EFT

What is EFT ?

Georgi, EFT, ARNPP 43(93) 209

- EFT = recipe to study observables at scale ℓ
  1. choose *appropriate* variables to describe *relevant* dynamics (*eg* use $\vec{E}, \vec{B}$ and currents for radio waves, electrons and photons at LEP)
  2. $\mathcal{O}(0)$ interactions : send parameters $\begin{cases} L \gg \ell & \to \infty \\ \delta \ll \ell & \to 0 \end{cases}$
  3. then perturb in ℓ/L and δ/ℓ

For LFV, take scale to be energy E : GeV $\to \Lambda_{NP}(\gtrsim$ few TeV)
(then do pert. theory in $E/\Lambda_{NP}, m/E$ for $m \ll E \ll \Lambda_{NP}$)
EFT $\Leftrightarrow$ add (yet another) peturbative expansion, in scale ratios, to SM calns. *If* E/Λ_{NP} "small", lowest order (dim 6) ok.

Ummm....renormalisation and EFT

- EFT an expansion in scale ratios, *eg* E/M_{NP}
- But...ummm...in QFT are loops, $p_{loop} \to \infty$, $p_{loop} \gg M_{NP}$?
- theorists disturbed by loops : $\begin{cases} \text{usually diverge on paper} \\ \text{usually finite tiny effects in real world} \end{cases}$

  $\Rightarrow$ machinery to regularise (loops) and renormalise (cplg cts)
- can extend regularis./renormalisation to dim > 4 ops of EFT

  ... *but EFT depends on details of how (eg put, or not, $M \gg E$ particles in loops ?)*

  $\star$ I use dimensional regularisation ; restricts the EFT I construct.

$\Rightarrow$ EFT as well-behaved a QFT as renormalisable models !
but (less arrogant =) less predictive, because knows only true things = what data and SM say...

parenthesis about EFT)

Models

for small Majorana masses

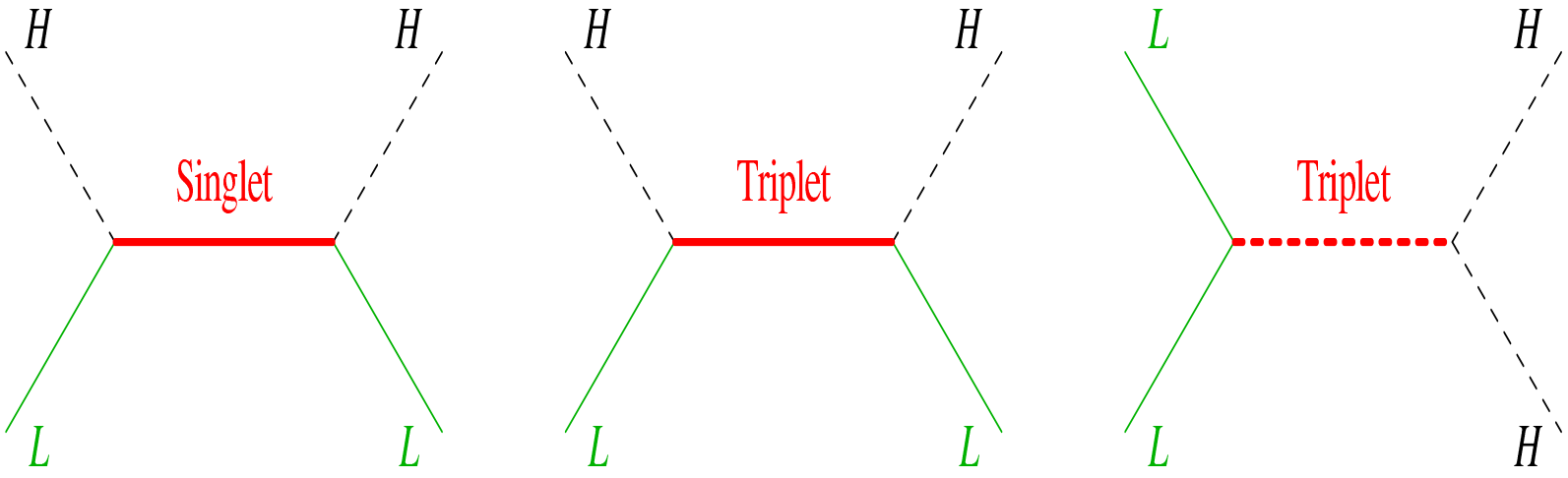
Tree-level Majorana mass models (*minimal*)

Heavy new particles (mass M) induce dimension 5 operator in $\mathcal{L}$:

$$\frac{K}{4M}[\ell H][\ell H] \to \nu\nu\frac{K\langle H_0\rangle^2}{4M}$$

Three possibilities at tree level :

SU(2) singlet fermions	triplet fermions	triplet scalars
Type I	Type III	Type II



Type 1 seesaw, one generation

Add to SM a singlet N with all renorm. interactions :

$$\mathcal{L}_{lep}^{Yuk} = h_e(\overline{\nu_L}, \overline{e_L}) \begin{pmatrix} -H^+ \\ H^{0*} \end{pmatrix} e_R + \lambda(\overline{\nu_L}, \overline{e_L}) \begin{pmatrix} H^0 \\ H^- \end{pmatrix} N + \frac{M}{2}\overline{N^c}N + h.c.$$

$$m_e\overline{e_L}e_R \qquad + m_D\overline{\nu_L}N \qquad + \frac{M}{2}\overline{N^c}N + h.c.$$

$\Rightarrow$ neutrino mass matrix :

$$\begin{pmatrix} \overline{\nu_L} & \overline{N^c} \end{pmatrix} \begin{bmatrix} 0 & m_D \\ m_D & M \end{bmatrix} \begin{pmatrix} \nu_L^c \\ N \end{pmatrix} \qquad (\nu_L^c \equiv (\nu_L)^c)$$

$\Rightarrow$ eigenvectors $\simeq$: ν_L with $m_\nu \sim \frac{m_D^2}{M}$, N with mass $\sim M$

A 2-chasing exercise

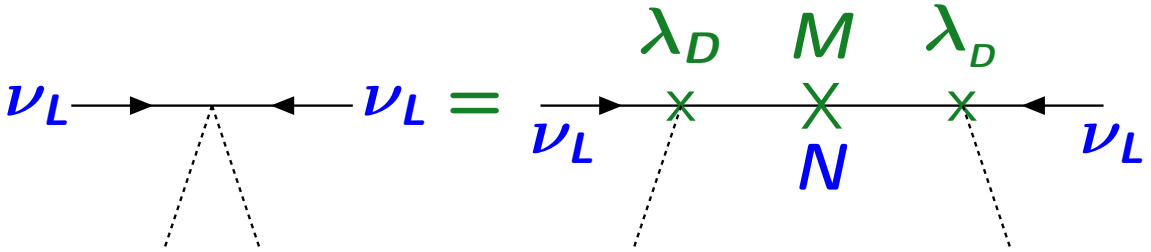
Majorana mass m_ν appears in low-E $\mathcal{L}$ as

$$\frac{m_\nu}{2}\nu_L\nu_L + h.c.$$

In type-1 seesaw, $m_\nu = m_D^2/M$
In SU(2)-invariant version, ($\frac{K}{M}$ is the 2H-2ℓ Feynman rule)

$$\mathcal{L} \supset \frac{K}{4M}(\ell H)(\ell H) + h.c. \Leftrightarrow m_\nu = \frac{K\langle H\rangle^2}{2M}$$

So need $\frac{K\langle H\rangle^2}{2M} = \frac{\lambda_D^2\langle H\rangle^2}{M}$ in type 1. But :



$$\frac{K}{M} = \frac{\lambda_D^2}{M}$$

ACK

A 2-chasing exercise

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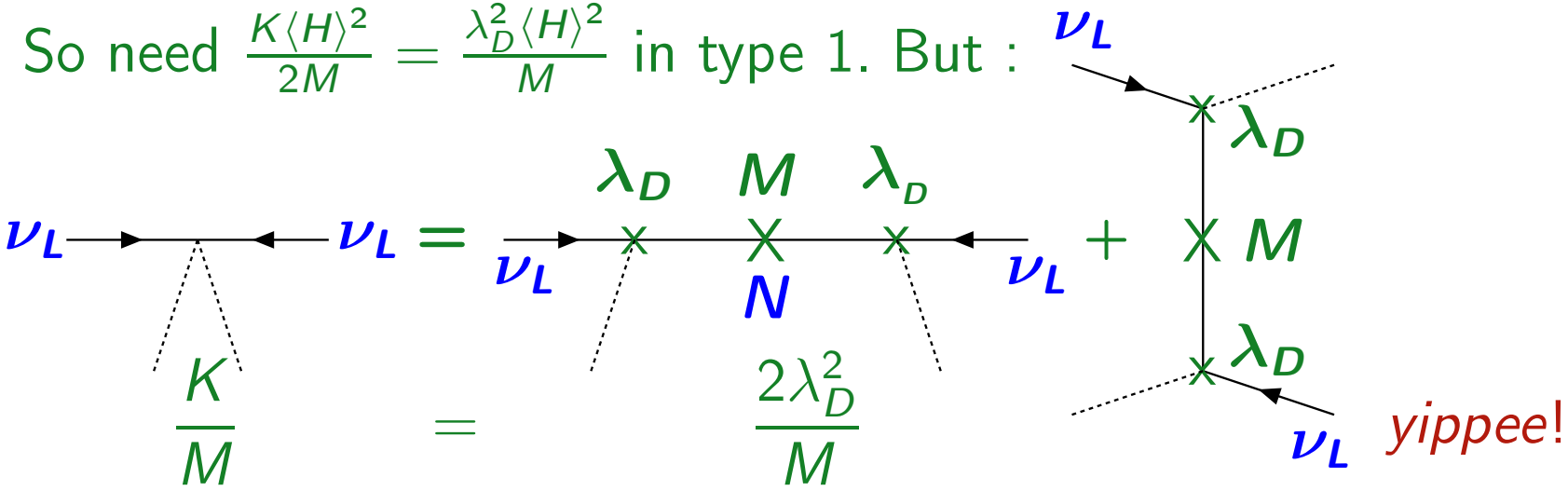


The type I seesaw

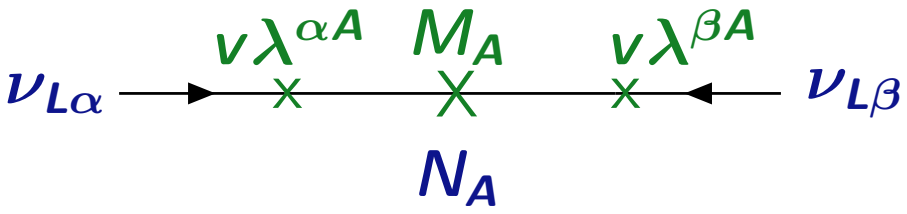
Minkowski, Yanagida
Gell-Mann Ramond Slansky

- add 3 singlet N to the SM in charged lepton and N mass bases :

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

add 18 parameters : M_1, M_2, M_3
18 - 3 (ℓ phases) in λ

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



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

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

$$\text{for} \quad \begin{array}{ll} \lambda \sim h_t\ , & M \sim 10^{15}\ \mathrm{GeV} \\ \lambda \sim 10^{-6}, & M \sim\ \mathrm{TeV} \end{array} \qquad \sim \quad .05\ \mathrm{eV}$$

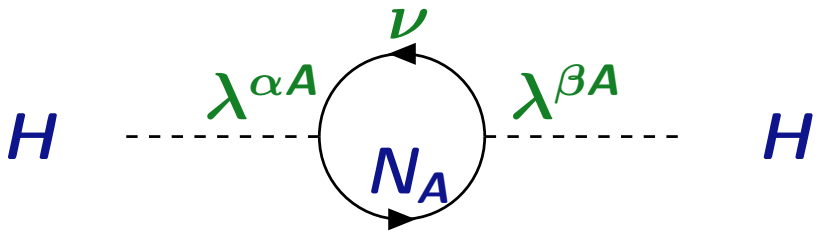
"natural" $m_\nu \ll m_f$, but N hard to detect ?

The type I seesaw + Higgs mass

- add 3 singlet N to the SM in charged lepton and N mass bases :

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

- at low scale, Higgs mass contribution



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

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

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

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

a low-scale tree model detectable at the LHC : the inverse seesaw

Valle
...

- add two singlets N, S per generation to the SM :

$$\mathcal{L} = \mathcal{L}_{SM} + \boldsymbol{\lambda}\overline{N}\ell \cdot H - \overline{N}MS - \tfrac{1}{2}\overline{S}\mu S^c$$

Dirac mass between N and S, small Majorana mass for S.
For $\mu = 0$, lepton number conserved, L=1 for ℓ, N, S^c, and $m_\nu = 0$ To check in 1-gen : mass matrix is

$$\begin{pmatrix} \overline{\nu_L} & \overline{N^c} & \overline{S} \end{pmatrix} \begin{bmatrix} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & 0 \end{bmatrix} \begin{pmatrix} \nu_L^c \\ N \\ S^c \end{pmatrix}$$

determinant vanishes.

massive ν_L in inverse seesaw

- add two singlets N, S per generation to the SM :

$$\mathcal{L} = \mathcal{L}_{SM} + \boldsymbol{\lambda}\overline{N}\ell \cdot H - \overline{N}MS - \tfrac{1}{2}\overline{S}\mu S^c$$

Dirac mass between N and S, small Majorana mass for S.
For $\mu \neq 0 \ll m_D \lesssim M$,

$$\begin{pmatrix} \overline{\nu_L} & \overline{N^c} & \overline{S} \end{pmatrix} \begin{bmatrix} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & \mu \end{bmatrix} \begin{pmatrix} \nu_L^c \\ N \\ S^c \end{pmatrix}$$

determinant $= \mu m_D^2 \Rightarrow$ masses $M, M, m_D^2\mu/M^2$

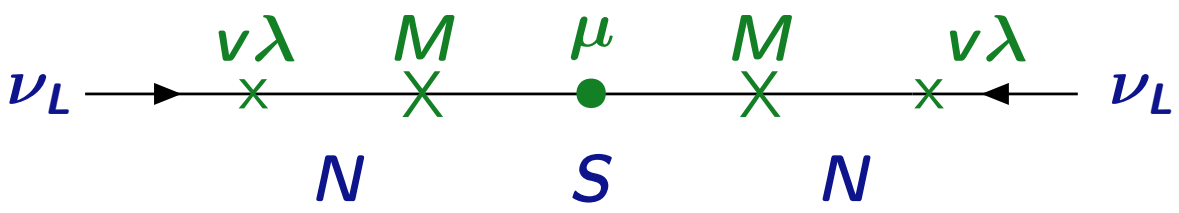
diagrammatic ν_L mass in inverse seesaw

- add two singlets N, S per generation to the SM :

$$\mathcal{L} = \mathcal{L}_{SM} + \boldsymbol{\lambda}\overline{N}\ell \cdot H - \overline{N}MS - \tfrac{1}{2}\overline{S}\mu S^c$$

Dirac mass between N and S, small Majorana mass for S.

- at low scale, light ν mass matrix



$$[m_\nu] \;=\; \boldsymbol{\lambda} M^{-1}\mu M^{-1}\boldsymbol{\lambda}^T v^2 \sim .05\ \mathrm{eV}$$

for $\lambda \sim 0.01$, $M \sim$ TeV, $\Rightarrow \mu \sim 10$ keV

Naturally small m_ν, and N @ TeV with $\mathcal{O}(1)$ yukawas.

Can neutrinos make the Universe we see ?

Leptogenesis

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.

Preambule

1. about "What the stars (and us) are made of" (5% of U)
   $\approx H \approx$ baryons
   not worry about lepton asymmetry : is (undetected) Cosmic Neutrino Background ...so how to measure asym ? ? ?
2. I am made of baryons(defn) ... observation... all matter we see is made of baryons (not anti-baryons)
3. quantify as ($s_0 \simeq 7 n_{\gamma,0}$)

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

PLANCK

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

Where did the matter excess come from ?

1. the U(niverse) is matter-anti-matter symmetric ?
   = islands of particles and anti-particles
   X no ! not see γs from annihilation

2. U was born that way...
   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...)
   - "60 e-folds" inflation $\equiv V_U \rightarrow > 10^{90} V_U$

     $(n_B - n_{\overline{B}}) \rightarrow 10^{-90}(n_B - n_{\overline{B}})$, s from ρ of inflation...

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

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

Sakharov

1. B violation : if Universe 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 : ...particles need to behave differently from anti-particles.
   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 $\rightarrow$ 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)

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

so, classically, there are conserved currents, and B and L are conserved. (So $B + L$ and $B - L$ are conserved.)

Good—proton appears stable :$\tau_p \gtrsim 10^{33}$ yrs ($\tau_U \sim 10^{10}$ yrs).

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.

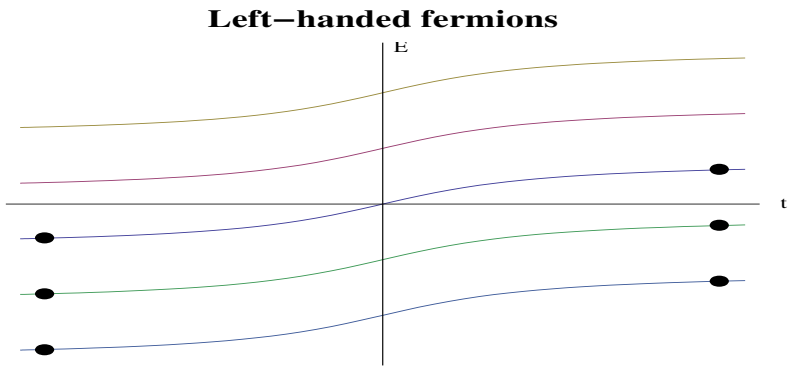
see Polyakov,
"Gauge Fields + Strings,"
6.3=qualitative effects of instantons

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

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

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

where integrating the RHS over space-time counts "winding number" of the SU(2) gauge field configuration.
$\Rightarrow$ Field configurations of non-zero winding number are sources of a doublet lepton and three (for colour) doublet quarks for each generation.



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 :

$$\Gamma_{\not{\mathrm{B+L}}} \sim \begin{array}{ll} e^{-m_W/T} & T < m_W \\ \alpha^5 T & T > m_W \end{array}$$

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

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

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

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 : $\not{B}$, $\not{C}\mathrm{P}$, $\not{T}\mathrm{E}$.
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 $\mathrm{B}\not{+}\mathrm{L}$)

Recall...the type I seesaw

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

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

M_I few GeV $\rightarrow 10^{15}$GeV, $\not{L}$. $\not{CP}$ in $\boldsymbol{\lambda}_{\alpha J} \in \boldsymbol{C}$.

Leptogenesis in the type 1 seesaw : usually a Fairy Tale

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

Once upon a time, a Universe was born.

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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 :
1 If its hot enough, a population of Ns appear(they like heat).
2 The temperature drops below M, N population decays away.
3 In the $\not{CP}$ and $\not{L}$ interactions of the N, an asymmetry 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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1 If its hot enough, a population of Ns appear(they like heat).
2 The temperature drops below M, 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 asymmetry escapes the 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).

Does it work ? Calculate something ?

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, $\eta = \not{T}\not{E}$ process/γ

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

Suppose at $T \gtrsim M_1$, a density $\sim T^3$ is produced.

Later, Lepton asym produced in $\not{C}\not{P}$ N decays, survives if not washed out by Inverse Decays = survives after ID out of equil :

$$\Gamma_{ID}(\phi\ell \to N) \simeq \Gamma_{decay} e^{-M_1/T} = \frac{[\lambda\lambda^\dagger]_{11} M_1}{8\pi} e^{-M_1/T} < \frac{10\,T^2}{m_{pl}}$$

Fraction N remaining at T_{ID} when ID turn off :

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

Estimate ϵ, the CP asymmetry in decays

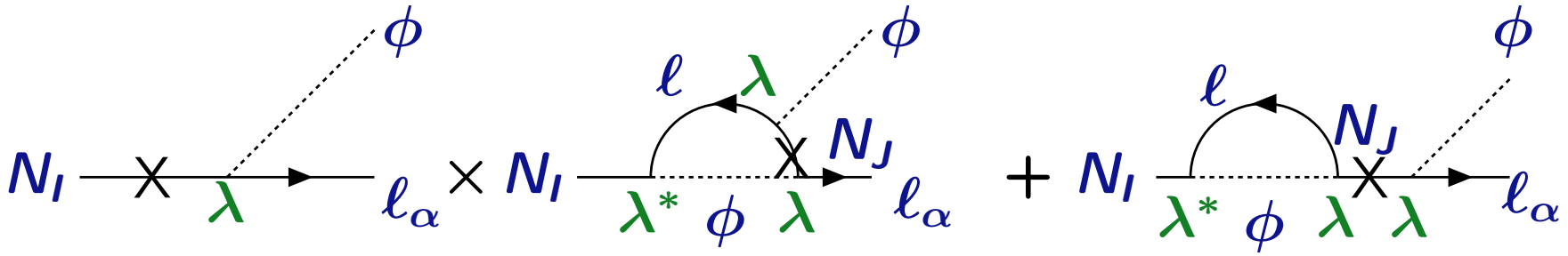
Kolb+Wolfram, NPB '80, Appendix

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)

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

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

$$\sim \text{ fraction } N \text{ decays producing excess lepton}$$



Just try to calculate ϵ_1 ?

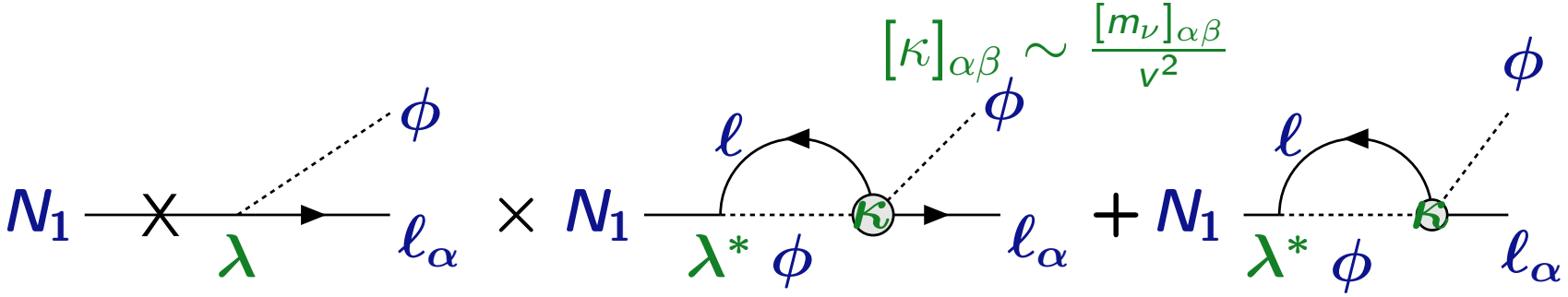
- asym at tree $\times$ loop, *if* $\not{CP}$ from complex cpling *and* on-shell particles in the loop (divergences cancel in diff, need Im part of Feynman param integrtn)

loops, unitarity and all that...(estimate ϵ, no loop caln)

Can use unitarity and CPT invariance of S-matrix to estimate ϵ from tree amplitudes.

Consider $M_1 \ll M_{2,3}$, asym from $\not{CP}$,$\not{L}$ decays of N_1 :

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



$$\epsilon_1 \sim \frac{1}{8\pi} \frac{\lambda^2 \kappa}{\lambda^2} M \quad < \quad \frac{3}{8\pi} \frac{m_\nu^{max} M_1}{v^2} \quad \sim 10^{-6} \frac{M_1}{10^9 \text{GeV}}$$

Estimate Y_B

Recall($s \sim g_* n_\gamma$, ϵ = lepton asym in decay $\eta = \not{T}\not{E}$ process/γ) :

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

$$\sim 10^{-3}\frac{H}{\Gamma}10^{-6}\frac{M_1}{10^9\text{GeV}}$$

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

?but give $\delta m_H^2 \gg m_H^2$?

do leptogenesis with $M_K < 10^7$ GeV ?

For $M_I \sim M_J \Leftrightarrow$ resonantly enhance ϵ ... up to $\epsilon \lesssim 1/8\pi$!
but need decays before Electroweak PT (to profit from sphalerons)... and ID out-of-equil :

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

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

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

Asaka + Shaposhnikov
Mesis Canetti
...

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

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

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

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

scenario :

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

Produce $\Delta L \gtrsim 10^{-5}$ via osc. and decay of $N_{2,3}$ after EPT

Can produce sufficient distribution of N_1 via osc.

tests :

$N_{2,3}$: beam dump, SHIP

N_1 as DM : X-rays from DM decay, WDM bounds (depend on momentum distribution)

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 $\lambda \overline{N} \ell \cdot \phi$

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)

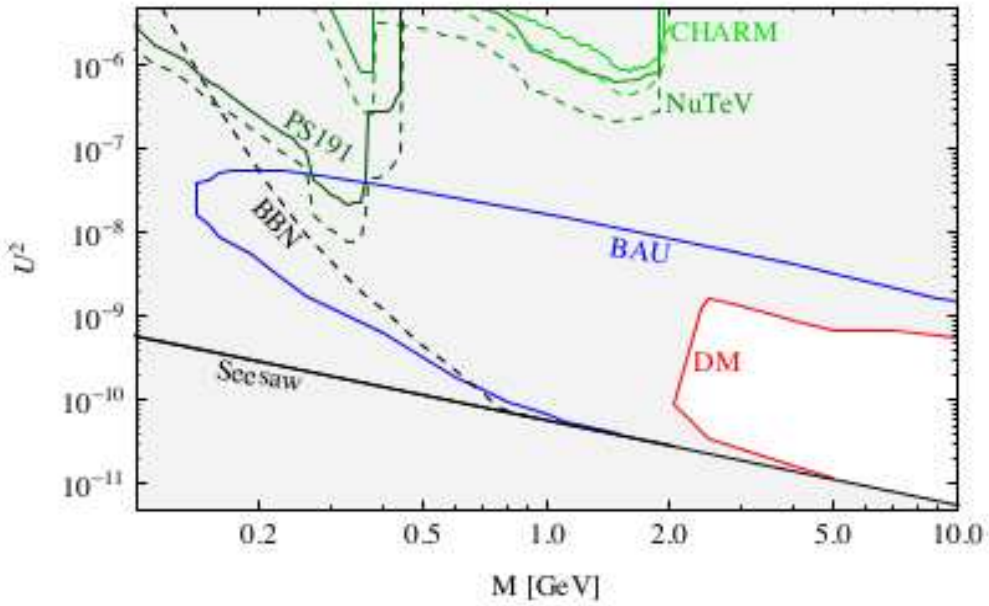
lepton number in $\ell_L + N_R$ is conserved (actually, $L_{SM}+$ helicity of N_I)

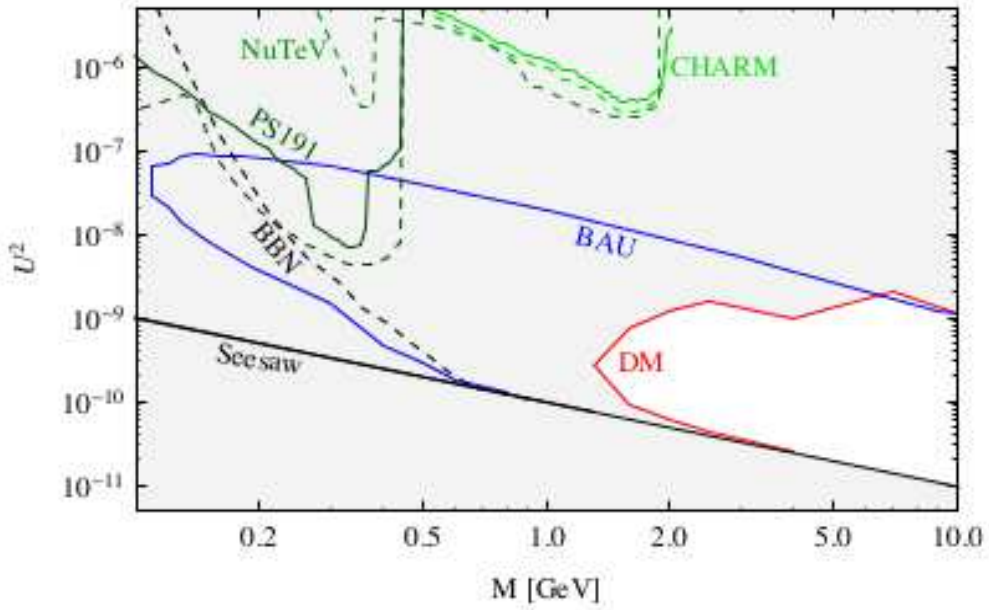
from $\tau_{osc} \to \tau_{EWPT}$, asyms in $\nu_{L\alpha}$ seed asyms in $N \longrightarrow$ asyms in $\nu_{L\alpha}$ (enough asym)

...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

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