Challenges for testing leptogenesis

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What does it mean to TEST a leptogenesis model?

Example: for the type1 seesaw (with R-handed neutrinos N)

Direct tests: Produce N's and measure the CP asymmetry in their decays

$$m_\nu \sim \frac{\lambda^2 v^2}{M_N} \sim \left(\frac{\lambda}{10^{-6}}\right)^2 \left(\frac{1\,\mathrm{TeV}}{M_N}\right) \sqrt{\Delta m^2_{atm}}$$

Not possible!

(Just measuring the CP asymmetry in decays would require a RH neutrino factory !)

Caveat: for any generic "TeV scale" lepto/baryogenesis model:

Even producing the "leptogenesis heavy states" does not mean "testing the lepto/baryogenesis mechanism".

In short: an unambiguous test would be verifying that **ALL** the three Sakharov conditions are satisfied ***quantitatively***.

Can we seek *indirect* evidences for Leptogenesis vs. Baryogenesis?

Regardless of the origin of the BAU:

At $T \gtrsim \Lambda_{EW}$ sphalerons relate B and L: $\Delta L \approx -2 \times \Delta B$

Sphaleron processes are "flavor blind":

Baryogenesis: $\Delta B \Rightarrow \Delta L$ thus necessarily $\Delta L_e = \Delta L_\mu = \Delta L_\tau$

Leptogenesis. $\Delta L \Rightarrow \Delta B$: almost unavoidably $\Delta L_e \neq \Delta L_\mu \neq \Delta L_\tau$

So it seems we *only* have to measure the lepton flavor asymmetries of the relic neutrino background .....

Unfortunately, today it is no more possible to reconstruct the original "LAU"

1. $T \lesssim 10\,\mathrm{MeV}$: L_α-violated (oscillations)

2. $T \lesssim m_\nu$: L-"evaporation"

neutrinos come at rest

handedness is lost

Today: $T_\nu^0 \sim 10^{-4}\,\mathrm{eV} \ll \Delta m^2_{atm,sol}$

Quite likely, for the next future the best we can hope for is to collect "*circumstantial evidences*" in favor of a leptogenesis mechanism, by proving that (some of) the Sakharov conditions are (likely to be) satisfied

1. L violation:

Is provided by the Majorana nature of the N's: $\ell_\alpha \phi \leftrightarrow N \leftrightarrow \bar{\ell}_\beta \bar{\phi}$

Experimentally: we hope to see $0\nu 2\beta$ decays

(requires IH or quasi degenerate ν's)

If m_ν is measured, say @ $\gtrsim 0.1\,\mathrm{eV}$ (Tritium Cosmology?)

and $0\nu 2\beta$ is not seen?

LeptoG would certainly be disfavored

(and the simplest realizations ruled out)

2. C & CP violation:

we hope to see $\not{CP}_L$ (Dirac phase δ)

(and likely we will)

If $\not{CP}_L$ is observed: Circumstantial evidence for LG (but not a final proof)

If $\not{CP}_L$ is not observed: LG is not disproved: $(\delta \sim 0, \pi \ldots)$

However, the value of the LG CP asymmetries cannot be *quantitatively* related to the phases of U_ν. No (predictive) relation between δ, α, β and the ΔB of the Universe.

About the issue of LG and low energy CP phases:

The flavor dependent decay CP asymmetry:

$$\epsilon_{1\alpha} \propto \sum_{j\neq 1} \mathrm{Im}\left\{ \frac{M_1}{M_j} \left(\lambda\lambda^\dagger\right)_{j1} \lambda_{j\alpha}\lambda^*_{1\alpha} \right\}$$

Use for the λ the CI parametrization

[A. Casas, A. Ibarra, NPB618 (2001) 171]

$$\lambda_{j\alpha} = \frac{1}{v}\sqrt{M_j} R_{j\beta}\sqrt{m_\beta}(U^\dagger)_{\beta\alpha} \quad \text{where} \quad RR^T = I \text{ (complex orthogonal)}$$

$$\lambda_{j\alpha}\lambda^*_{1\alpha}\left(\lambda\lambda^\dagger\right)_{j1} = \frac{M_1 M_j}{v^4}\left(\sum_\beta m_\beta R^*_{1\beta}R_{j\beta}\right)\left(\sum_{\rho\sigma}\sqrt{m_\rho m_\sigma} R_{j\sigma}R^*_{1\rho}U^*_{\alpha\sigma}U_{\alpha\rho}\right)$$

$$\sum_\alpha \longrightarrow \frac{M_1 M_j}{v^4}\left(\sum_\beta m_\beta R^*_{1\beta}R_{j\beta}\right)^2$$

If the matrix **R** is real orthogonal:

(1) $\varepsilon_1 = \Sigma_\alpha \varepsilon_{1\alpha} = 0$ (Purely Flavored LG);

(2) $\varepsilon_{1\alpha}$ (and LG) depend just on U !

EN, Y.Nir, E.Roulet, J.Racker *JHEP 0601 (2006) 164*

3. Out of equilibrium dynamics in the early Universe:

(apparently the most difficult)

Out-of-Eq. condition in the Seesaw: When the temperat. drops to $T \approx M_N$ the Universe must be at most one N_R-lifetime old: $H^{-1}(M_N) \leq \tau_N$;
And if the N have to be produced thermally (by ID): $H^{-1}(M_N) \approx \tau_N$

$$\Gamma_N = \frac{M}{16\pi} \left(\lambda \lambda^\dagger\right)_{11}$$

$$H\big|_M = \sqrt{\frac{8\pi G_N\, \rho(M)}{3}} \simeq 17 \cdot \frac{M^2}{M_P}$$

Rescale both by $16\pi \frac{v^2}{M^2}$

$$\tilde{m} = \frac{v^2}{M} \left(\lambda \lambda^\dagger\right)_{11}$$

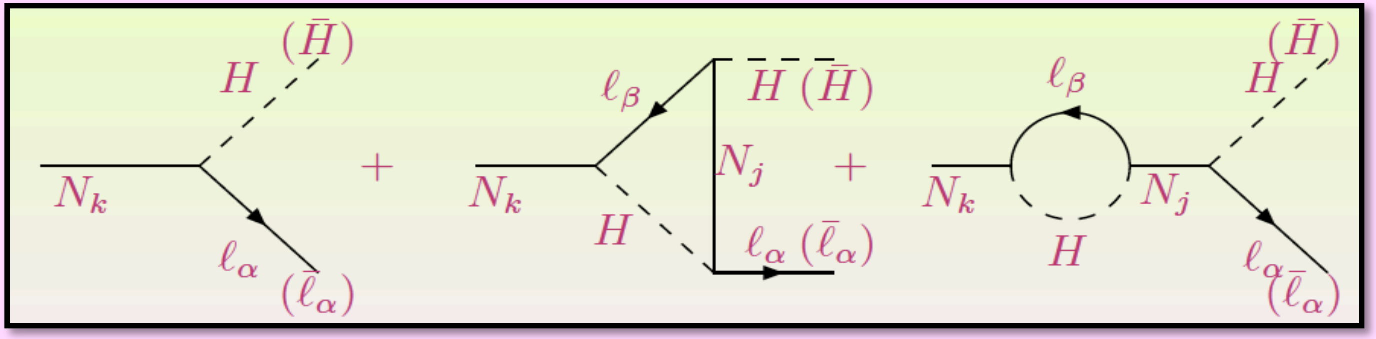
$$m_* \approx 10^{-3} \mathrm{eV}$$

Quantitatively: $\tilde{m} \sim m_* \; (\times 10^{\pm 2})$ can be OK

Thus $\tilde{m}(\geq m_1) \approx \sqrt{\Delta m^2_\odot}, \sqrt{\Delta m^2_\oplus}$ is an optimal size to realize Sakharov III

Sakharov II: CP violation (in relation with ν masses ...)

Computation of $\epsilon_\alpha = \frac{\Gamma_{\ell_\alpha} - \Gamma_{\bar\ell_\alpha}}{\Gamma_N}$



It is useful to present the result as an expansion in $M_1/M_j << 1$:

$$\epsilon_\alpha = \frac{-1}{8\pi(\lambda\lambda^\dagger)_{11}} \sum_{j\neq 1} \mathrm{Im}\left\{ \lambda_{j\alpha}\lambda^*_{1\alpha} \left[\underbrace{\frac{3M_1}{2M_j}(\lambda\lambda^\dagger)_{j1}} + \underbrace{\frac{M_1^2}{M_j^2}(\lambda\lambda^\dagger)_{1j}} + \underbrace{\frac{5M_1^3}{6M_j^3}(\lambda\lambda^\dagger)_{j1}} + \ldots \right] \right\}$$

$\not{L}: D_5 = (\ell\phi)^2 \qquad L: D_6 = (\bar\ell\phi^*)\not\partial(\ell\phi) \qquad \not{L}: D_7 = (\ell\phi)\partial^2(\ell\phi)$

$D_5 \Rightarrow$ neutrino mass operator; $D_6 \Rightarrow$ non unitarity in lepton mixing; $D_7 \Rightarrow$ spoils the DI bound.

Sakharov II:

The leading contribution to $\varepsilon^{(D5)}$ can be bounded in terms of M_1 and m_ν

DI: $\left|\epsilon^{(D_5)}\right| = \left|\sum_\alpha \epsilon_\alpha^{(D_5)}\right| \leq \frac{3}{16\pi}\frac{M_1}{v^2}(m_3 - m_1) \xrightarrow{m_3 \simeq m_1} \left|\epsilon^{(D_5)}\right| \leq \frac{3}{16\pi}\frac{\Delta m_\oplus^2}{2v^2}\frac{M_1}{m_3}$

[S. Davidson & A. Ibarra, PLB 535 (2002)]

Requiring $\varepsilon^{(D5)} > 10^{-6}$ implies: **$M_1 \geq 10^8 - 10^9$ GeV**

Considering also $\Delta L = 2$ washouts we can bound m_{ν_3} from above

$$m_{\nu_3}^{\max} = 0.10\,\mathrm{eV}$$

(The limit holds if some assumptions are satisfied)

[W. Buchmüller, P. Di Bari& M. Plümacher; S. Blanchet & P. Di Bari;]
[T. Hambye,Y. Lin, A. Notari, M. Papucci & A. Strumia; …]

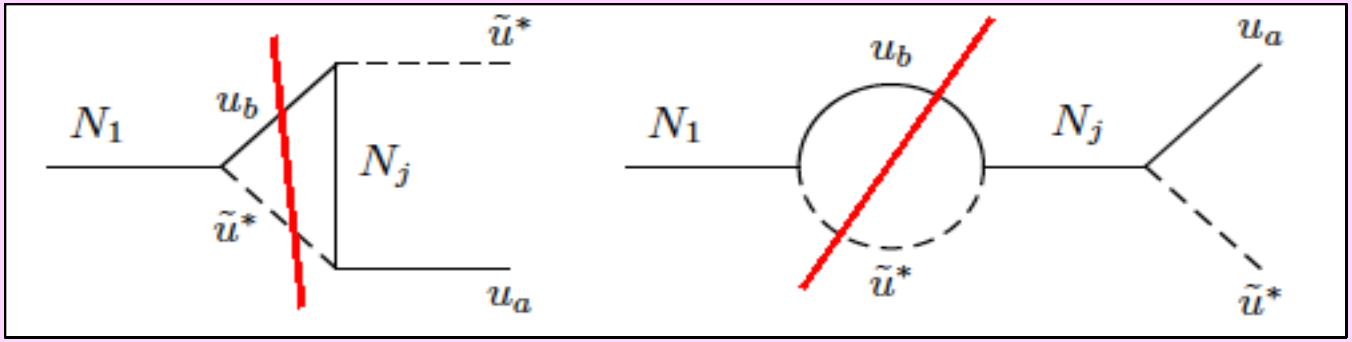
To lower the LG scale we have to abandon connections with m_ν ☹

Even abandoning the $m_\nu - \varepsilon_{CP}$ connection, in general it is still not possible to reach scales much below $M_N \approx 10^7 GeV$

The no-go condition is a consequence of intrinsic requirements for the CP-violating loop diagrams:

1. *Hard rescattering CP even phase: => loop states can go on shell*

2. *L conserving loops do not yield any CP asymmetry* [D.Nanopoulos, S.Weinberg PRD20 (1979)]
which means that L must be violated inside the loop



So the cuts generate $\Delta L = 2$ *t-* and *s-* washout scattering diagrams

The argument is quite general *(although not very well known)*

Consider a decaying particle $X_1 \rightarrow Y, Z\ (Y^*, Z^*)$ [$f \rightarrow f\,s$, $s \rightarrow f\,f$, $s \rightarrow s\,s$]

$$\gamma^{(fs)}(YZ \leftrightarrow \bar{Y}\bar{Z}) \simeq \frac{1}{\pi^3}\frac{T^3}{M_{X_2}^2}|g_2|^4 \rightarrow \frac{64}{\pi} M_{X_1}\left(\epsilon_{X_1}^{(fs)}\right)^2$$

$$\gamma^{(ff')}(YZ \leftrightarrow \bar{Y}\bar{Z}) \simeq \frac{1}{\pi^3}\frac{T^5}{M_{X_2}^4}|g_2|^4 \rightarrow \frac{64}{\pi} M_{X_1}\left(\epsilon_{X_1}^{(ff')}\right)^2$$

$$\gamma^{(ss')}(YZ \leftrightarrow \bar{Y}\bar{Z}) \simeq \frac{1}{\pi^3}\frac{T}{M_{X_2}^4}|g_2|^4 \rightarrow \frac{64}{\pi} M_{X_1}\left(\epsilon_{X_1}^{(ss')}\right)^2$$

Requiring: $\gamma(YZ \leftrightarrow \bar{Y}\bar{Z}) \lesssim H(M_{X_1})$ ➔ $M_{X_1} \gtrsim 10^{19} \times \epsilon_{X_1}^2$ GeV

D. Aristizabal Sierra, C.S. Fong, EN, E. Peinado, JCAP 1402, (2014) 013
J. Racker, JCAP 1403, (2014) 025, in the *Inert Higgs doublet model*

Possible ways to circumvent the argument:

$$\gamma_{\Delta=2} \not\propto \epsilon_X^2$$

Spoil the proportionality:

1. *by enhancing the CP asymmetry* ε_{X_1}
2. *by suppressing the* $\Delta=2$ *washouts*

1. For quasi degenerate N_R's ($\Delta M/M \ll 1$) ε_{X_1} can be resonantly enhanced (maximal effect when $\Delta M \approx \Gamma_N$)

A. Pilaftis and T.E. Underwood, NPB692 (2004) 303

Another possibility relies on resonant CP asymmetry enhancement in $H \to \ell N_R$ decays

(CP asymmetry induced by thermal effects)

T.Hambye, D.Teresi, arXiv:1606.00017

2. Suppress the washouts with late/delayed decays

(a.) if $m_{Y,Z} << M_{X_1}$: since the washouts $\gamma_{\Delta=2} \approx (T/M_{X_2})^n$
just assume a long lifetime $\Gamma_X << H$ (i.e. $T_{decay} << M_{X_{1,2}}$)
(this requires an additional mechanism for X production)

(b.) or assume $m_{Y,(Z)} \approx M_{X_1}$ in order to suppress exponentially the final state particle densities at $n_{Y,(Z)}$ at T not much below M_{X_1}.
(This was applied to the inert Higgs doublet model showing that it can work)

J. Racker, JCAP 1403, (2014)025

All these solutions require a certain level of tuning in the choice of model parameters, at the cost of simplicity/aesthetics/naturalness

CONCLUSIONS

- LG *from decays* is intrinsically a high energy mechanism. To realize it at low scales requires abandoning the m_ν–Sakharov II connection, and often also the m_ν–Sakharov III (plus inventing non-trivial new mechanisms).

- Discovery of L violation and of CP violation in the lepton sector will indeed reinforce our confidence that LG is *qualitatively* adecuate.
  However, the issue of *quantitative* verifications will remain.

- Presently, I cannot see any way through which LG could parallel, for example, the quantitative success of BBN.
  (i.e.: predicting cosmological abundances from measurements in the labs.)

THANKS

To lower the LG scale we have to abandon connections with m_ν ☹

A simple attempt: Couple N_R to a different SM fermion: (ℓ), e, Q, u, d

C.S.Fong et.al. JHEP 1308, 104

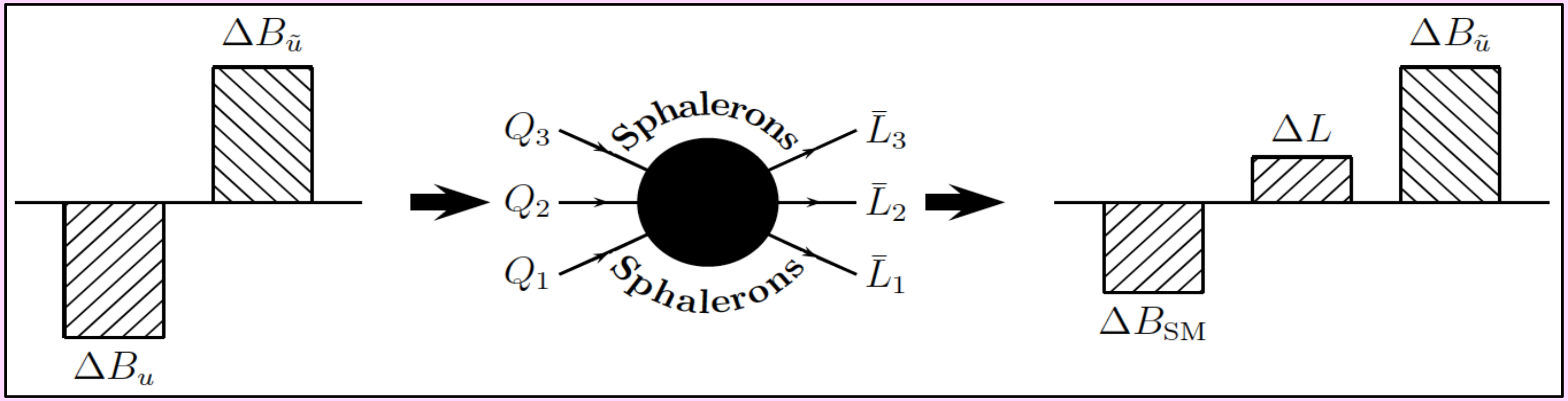
	Scalar field	Couplings	B	L	ΔB	ΔL
✔	$\tilde{\ell}$	$\bar{\ell} e\,(\epsilon \tilde{\ell}^*),\ \bar{Q} d\,(\epsilon \tilde{\ell}^*),\ \bar{Q} u\,\tilde{\ell}$	0	0	0	-1
✔	$\tilde{e}$	$\bar{\ell}(\epsilon \ell^c)\,\tilde{e}$	0	$+2$	0	$+1$
✔	$\tilde{Q}$	$\bar{\ell} d\,(\epsilon \tilde{Q}^*)$	$+1/3$	-1	0	-1
☑	$\tilde{u}$	~~$\overline{d^c} d\,\tilde{u}$~~ $U(1)_B$	$+1/3$	0	0	0
✖	$\tilde{d}$	$\bar{\ell}(\epsilon Q^c)\,\tilde{d},\ \overline{Q^c}(\epsilon Q)\,\tilde{d},\ \bar{u} e^c\,\tilde{d},\ \overline{u^c} d\,\tilde{d}$	–	–	–	–

$N \to e\ \tilde{e}$

$N \to Q\ \tilde{Q}$

A model for direct Baryogenesis.

(And an attempt to lower as much as possible the M_N scale)



D. Aristizabal Sierra, et.al. JCAP 1402, 013

After EWSB the colored scalar decay via N-ν mixing injecting their associated ΔB

$$\tilde{u} \rightarrow u\nu$$

Special properties of this setup:

- After EWSB, a ΔB is generated, and with the ***same sign*** of ΔL

- Observation of same sign dileptons *pp* -> $\ell^{\pm}\ell^{\pm}$ *jj* at LHC signaling $\Delta L=2$ violation does not invalidate the model

  F.F. Deppisch, J.Harz & M.Hirsch PRL 112(2014) 221601

- $\Delta L \neq 0$ processes can even attain chemical equilibrium

  (asymmetry protected by hypercharge - A. Antaramian, L.J.Hall & A.Rasin PRD 49(1994) 381)

However, we find that still it is not possible to reach Scales much below $M_N \approx 10^7 GeV$