LEPTOGENESIS

NEWS

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DISCLAIMER: this is NOT a comprehensive review of leptogenesis

See for instance:

Buchmüller, Peccei, Yanagida, 2005

Davidson, Nardi, Nir, 2008

Fong, Nardi, Riotto, 2012

Outline

- Introduction
- Leptogenesis basics and recent progress
- Low scale leptogenesis beyond the seesaw
- Leptogenesis and DM
- Leptogenesis via sterile neutrino oscillations
- And the LHC/$0\nu\beta\beta$ decay ?
- Summary and outlook

I. Introduction

- Asymmetric Universe: negligible abundance of antimatter w.r.t. matter
- Baryon density: determined from
  - Big Bang Nucleosynthesis: primordial abundances of light elements (D, ^{3}He, ^{4}He, ^{7}Li) depend on n_B/s
  - CMB anisotropies

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} \simeq \frac{n_B}{s} \simeq 8.5 \times 10^{-11}$$

Impressive consistency between both determinations, completely independent !

- Baryon asymmetry
  - nucleons and antinucleons were in thermal equilibrium up to $T_{fo} \approx 20$ MeV, when $\Gamma_{ann} < H$
  - If the Universe were locally baryon-symmetric:

    $Y_{Bfo} < 10^{-20}$

- Sakharov's conditions to dinamically generate the baryon asymmetry (BAU)
  - Baryon number violation
  - C and CP violation
  - Departure from thermal equilibrium

II. Leptogenesis basics and recent progress

- BAU generated in the decay of heavy Majorana neutrinos: Fukugita, Yanagida, 1986

  - Out of equilibrium decay
  - L and CP violating interactions ➔ lepton asymmetry, ΔL
  - (B+L)-violating, but (B-L) conserving, non-perturbative sphaleron interactions ΔL ➔ ΔB

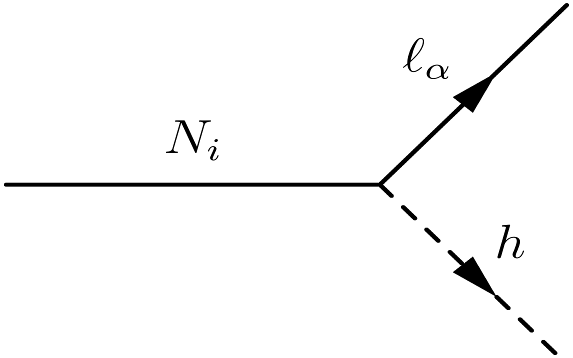
- Non-equilibrium process ➔ Boltzmann eqs.

$$\frac{dY_{N_1}}{dz} = -\left(\frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1\right)(D+S)$$

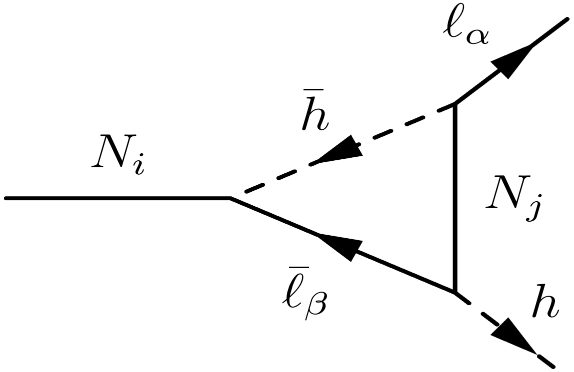
$$\frac{dY_{B-L}}{dz} = -\epsilon\left(\frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1\right) D - Y_{B-L} W$$

$$z \equiv M_1/T$$

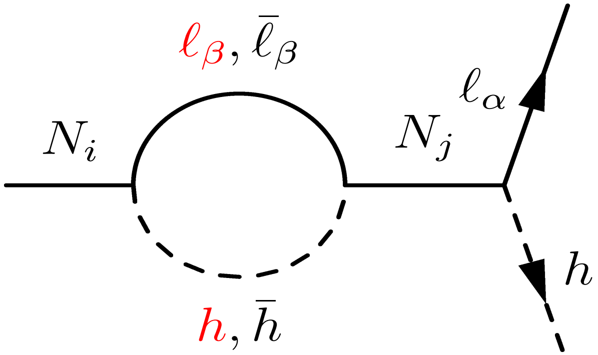
$$\epsilon = \sum_\alpha \epsilon_{\alpha 1} = \sum_\alpha \frac{\Gamma(N_1 \to \ell_\alpha h) - \Gamma(N_1 \to \bar{\ell}_\alpha \bar{h})}{\sum_\beta \Gamma(N_1 \to \ell_\beta h) + \Gamma(N_1 \to \bar{\ell}_\beta \bar{h})}$$



(e) Tree



(f) Vertex



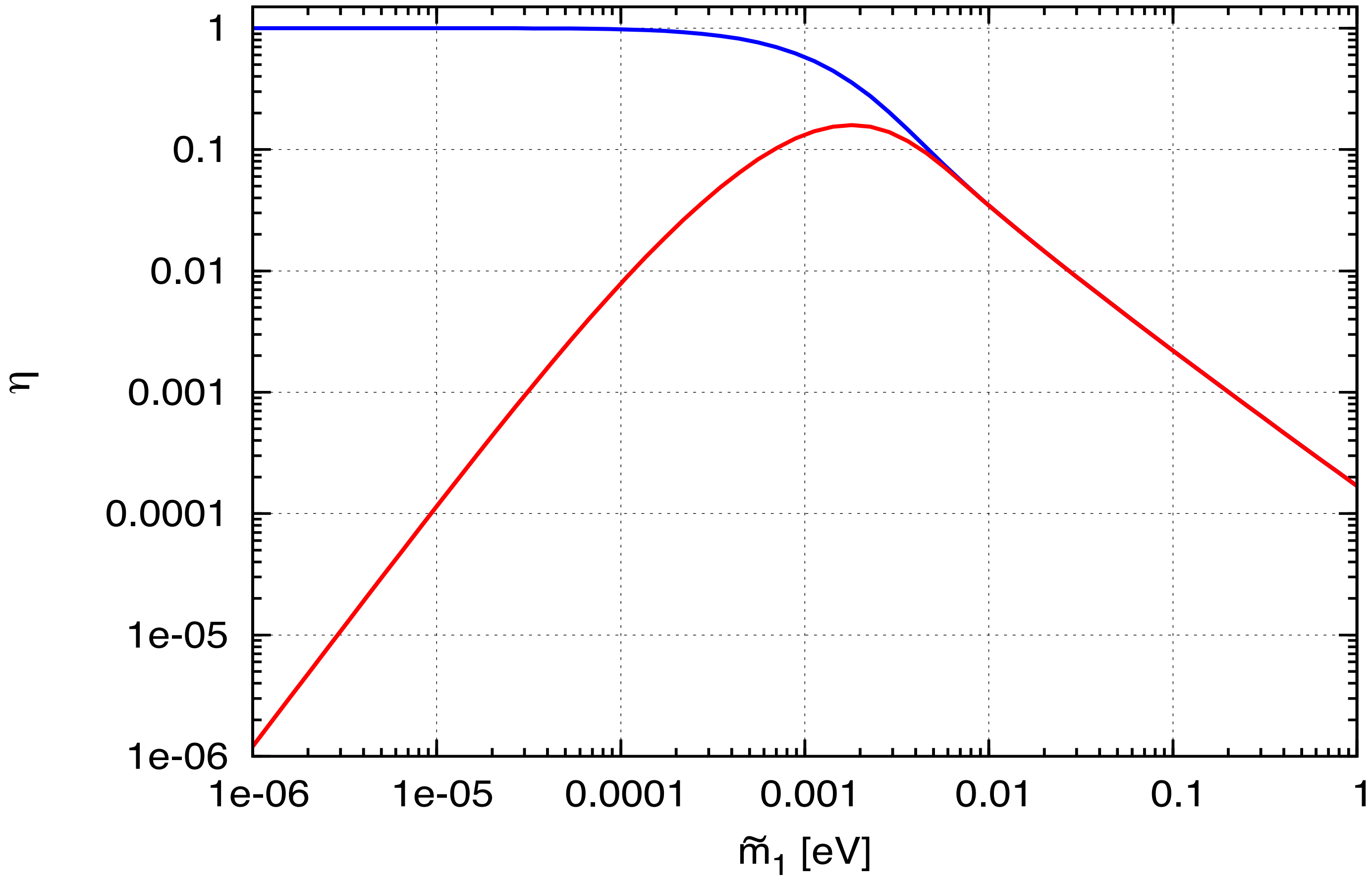
(g) Wave

- Final baryon asymmetry:

$$Y_B = -\kappa\,\epsilon\,\eta$$

$$\kappa = \frac{28}{79} Y_{N_1}^{eq}(T \gg M_1) \sim 10^{-3}$$

η = efficiency : $0 \leq \eta \leq 1$



🟥 $Y_N^i = 0$ 🟦 $Y_N^i = Y_N^{eq}$ **J. Racker**

$$\tilde{m}_1 \equiv \frac{(\lambda^\dagger \lambda)_{11} v^2}{M_1}$$

Related to the contribution of N_1 to light neutrino masses

- η maximum for

$$\tilde{m}_1 = m_* = \frac{16}{3\sqrt{5}}\pi^{5/2}\sqrt{g_*}\frac{v^2}{M_P} \sim 10^{-3}\,\mathrm{eV}$$

m* , defined by: $$\frac{\Gamma_N}{H(T=M_1)} = \frac{\tilde{m}_1}{m_*}$$

determines the amount of departure from thermal equilibrium and the strength of the washouts:

$\tilde{m}_1 \gg m_*$ ➔ strong washout:

- independence of initial conditions, $\eta \propto 1/\tilde{m}_1$

$\tilde{m}_1 \ll m_*$ ➔ weak washout:

- depends on initial conditions, if $Y_N^i = 0 \ \rightarrow \eta \propto \tilde{m}_1^2$

- Hierarchical heavy neutrinos: $\epsilon \sim \frac{3}{16\pi} \frac{\lambda^2_{\alpha 2}}{M_2} M_1$
- Connection to light neutrino masses (type I seesaw):

$$|\epsilon| \leq \epsilon_{DI} = \frac{3}{16\pi} \frac{M_1}{v^2} (m_3 - m_1)$$

Davidson, Ibarra, 2002

➔ $M_1 \gtrsim 10^9\,\mathrm{GeV}$

Detailed numerical analysis solving BEs:

➔ $M_1 \gtrsim (4\times)10^8\mathrm{GeV}$ for fine-tuned regions

Hambye et al. 2004

➔ bound on light neutrino masses, $m_\nu < 0.15$ eV

Buchmüller, Di Bari, Plümacher, 2004

Flavour effects:

- At $T \lesssim 10^{12}$ GeV, the τ Yukawa interaction is fast, and there are (in general) 2 lepton flavour asymmetries evolving almost independently
- At $T \lesssim 10^{9}$ GeV, both τ and μ Yukawa interactions are in equilibrium ➔ 3 independent lepton flavour asymmetries, $Y_{\Delta(B/3-L\alpha)}$

Barbieri et al. 2000

Endoh et al. 2004

Abada et al. 2006

Nardi et al. 2006

Some consequences:

★Flavoured asymmetries ε_α depend on U_{PMNS} phases although in general leptogenesis is “insensitive” to them, even in SUSY Davidson, Garayoa, Palorini, NR, 2007

★Bound on light neutrino masses $m_\nu < 0.15$ eV evaded

★N_2 leptogenesis can survive N_1 washouts more easily:

➔ relevant for SO(10) models which predict $M_1 << 10^9$ GeV

★Leptogenesis possible with $\epsilon = \sum \epsilon_\alpha = 0$

➔ relevant for models with small$^\alpha$B-L violation (inverse seesaw, ISS)

$$\epsilon_{\alpha i} \equiv \frac{\Gamma(N_i \to \ell_\alpha h) - \Gamma(N_i \to \bar{\ell}_\alpha \bar{h})}{\sum_\beta \Gamma(N_i \to \ell_\beta h) + \Gamma(N_i \to \bar{\ell}_\beta \bar{h})} = \epsilon^{\not{L}}_{\alpha i} + \epsilon^{L}_{\alpha i}$$

where:

Covi, Roulet, Vissani, 1996

$$\epsilon^{\not{L}}_{\alpha i} = \sum_{j \neq i} f(a_j) \mathrm{Im}[\lambda^*_{\alpha j} \lambda_{\alpha i} (\lambda^\dagger \lambda)_{ji}]$$

$$a_j \equiv M_j^2 / M_i^2$$

$$\epsilon^{L}_{\alpha i} = \sum_{j \neq i} g(a_j) \mathrm{Im}[\lambda^*_{\alpha j} \lambda_{\alpha i} (\lambda^\dagger \lambda)_{ij}]$$

related to L conserving d=6 operators ➔ escape the DI bound because they are not linked to neutrino masses (LNV d=5 Weinberg operator)

- $\sum_{\alpha} \epsilon^{L}_{\alpha i} = 0$ ➔ flavour effects mandatory

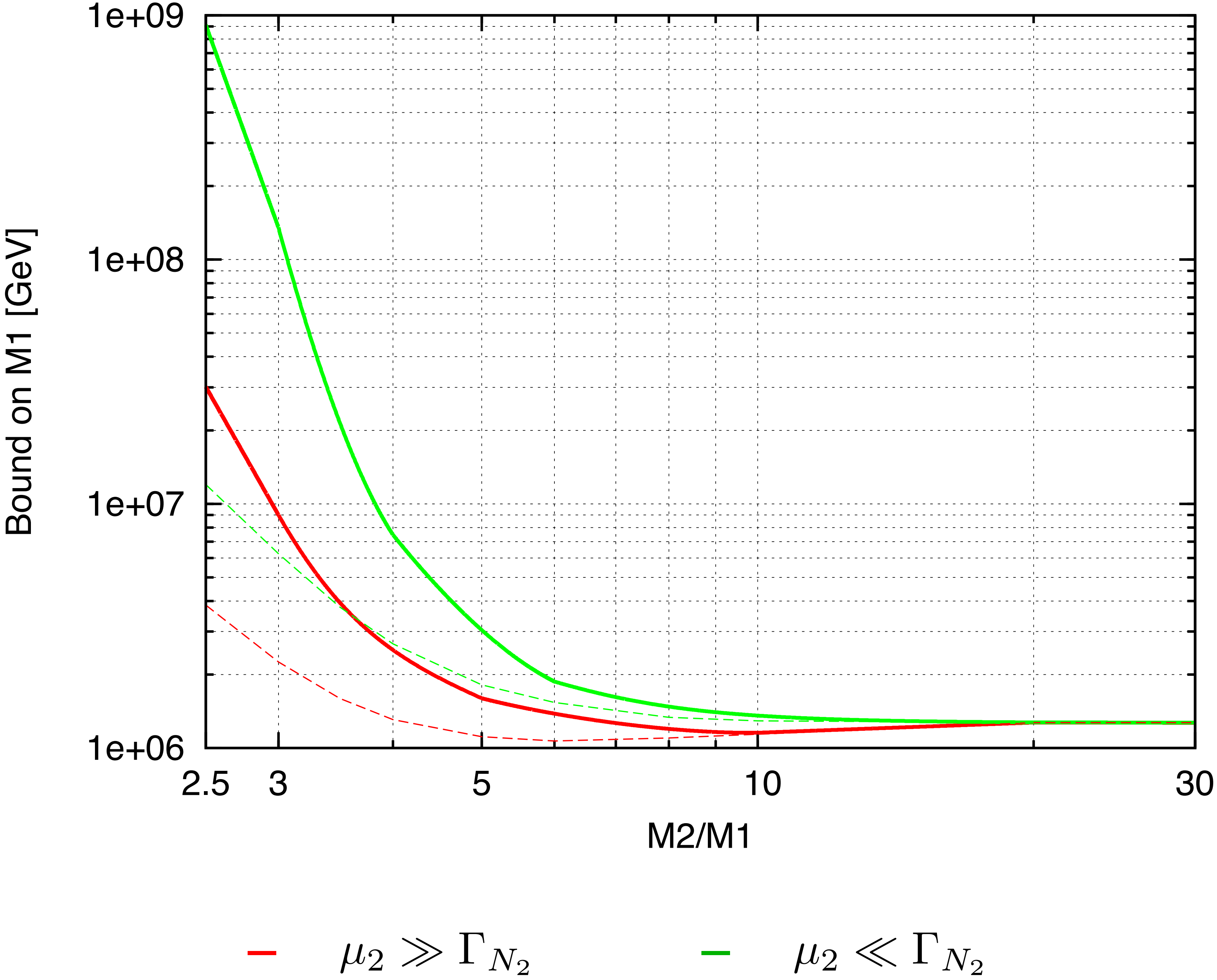
- Large $\lambda_{\alpha 2}$ Yukawa couplings ➔ N$_2$ pseudo-Dirac:
  $M_{\pm} = M \pm \mu_2$

- Crucial L-conserving but LFV interactions, mediated by N$_2$, should be taken into account:

$$\ell_\beta h \to \ell_\alpha h \qquad \ell_\beta \bar{h} \to \ell_\alpha \bar{h} \qquad h\bar{h} \to \ell_\alpha \bar{\ell}_\beta$$

Antusch et al. 2010

Racker, Peña, NR, 2012


1e+09
1e+08
1e+07
1e+06
Bound on M1 [GeV]
2.5
3
5
10
30
M2/M1
$\mu_2 \gg \Gamma_{N_2}$
$\mu_2 \ll \Gamma_{N_2}$

- Resonant leptogenesis: enhancement of the CP asymmetry for degenerate neutrinos, $M_2 - M_1 \approx \Gamma_2$

$$|\epsilon| \sim \frac{1}{2} \frac{\mathrm{Im}[(\lambda^\dagger\lambda)^2_{21}]}{(\lambda^\dagger\lambda)_{11}(\lambda^\dagger\lambda)_{22}} \leq \frac{1}{2}$$

Covi, Roulet, 1997; Pilaftsis, 1997; Pilaftsis, Underwood 2004

➔ EW scale e-,μ-,τ- leptogenesis with observable LFV

Pilaftsis 2005; Deppisch, Pilaftsis 2011

- Approximate flavour symmetries + universal RHN masses at the GUT scale ➔ heavy neutrino mass splittings radiatively generated

Non-equilibrium QFT:

Kadanoff-Baym equations for spectral functions and statistical propagators of leptons and Majorana neutrinos Anisimov et al., 2011; Drewes et al. 2013

- ★ Relevant in the weak washout regime

- ★ Very important for resonant leptogenesis: supression of about one order of magnitude wrt previous calculations Garny, et al., 2013

- If $M_2 - M_1 \approx \Gamma_2$ ➔ sterile neutrino oscillations
- Taken into account using "Flavour covariant transport equations" ➔ density matrix formalism

$$\dot{\rho} = -i[H, \rho]$$

Dev et al., 2014 (109 p.)

- Identify mixing contribution from diagonal ρ_N and heavy neutrino oscillation contribution from off-diagonal $(\rho_N)_{12}$
- One order of magnitude enhancement
- Also in the Kadanoff-Baym approach Dev et al., 2015

III. Low scale leptogenesis beyond the seesaw

Baryogenesis from particle decays or annihilations at low T (TeV scale)

- Potentially testable mechanisms for baryogenesis
- Avoid hierarchy and gravitino (in SUSY) problems
- High scale baryogenesis disfavored if L violating processes are observed at LHC

  [more later]
- Common origin of dark and baryon matter?

$$\frac{\Omega_{DM}}{\Omega_B} \approx 5$$

- Radiative neutrino mass models (like inert doublet)

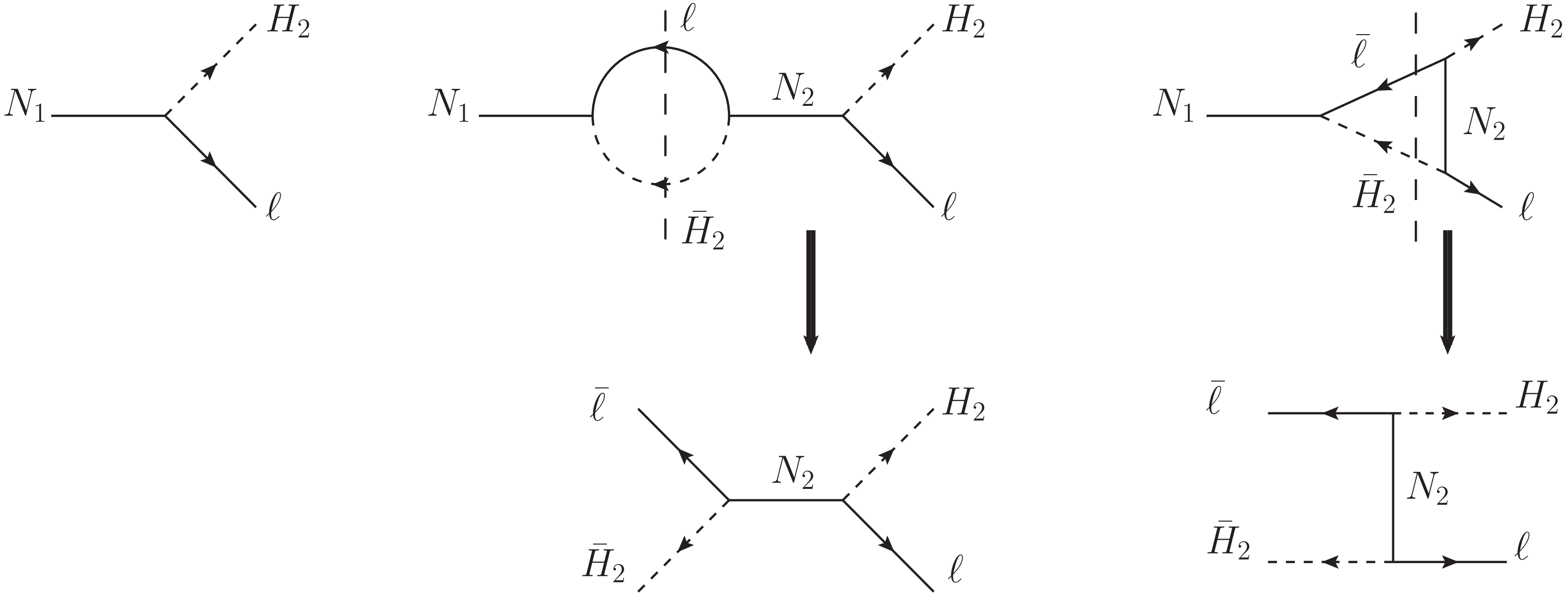
  → no DI bound on ε

- Generic problem of baryogenesis at low scales, independent of the connection to neutrino masses: fast washout of the asymmetries

$$\epsilon \propto \frac{\lambda_{\alpha 2}^2}{M_2} M_1$$

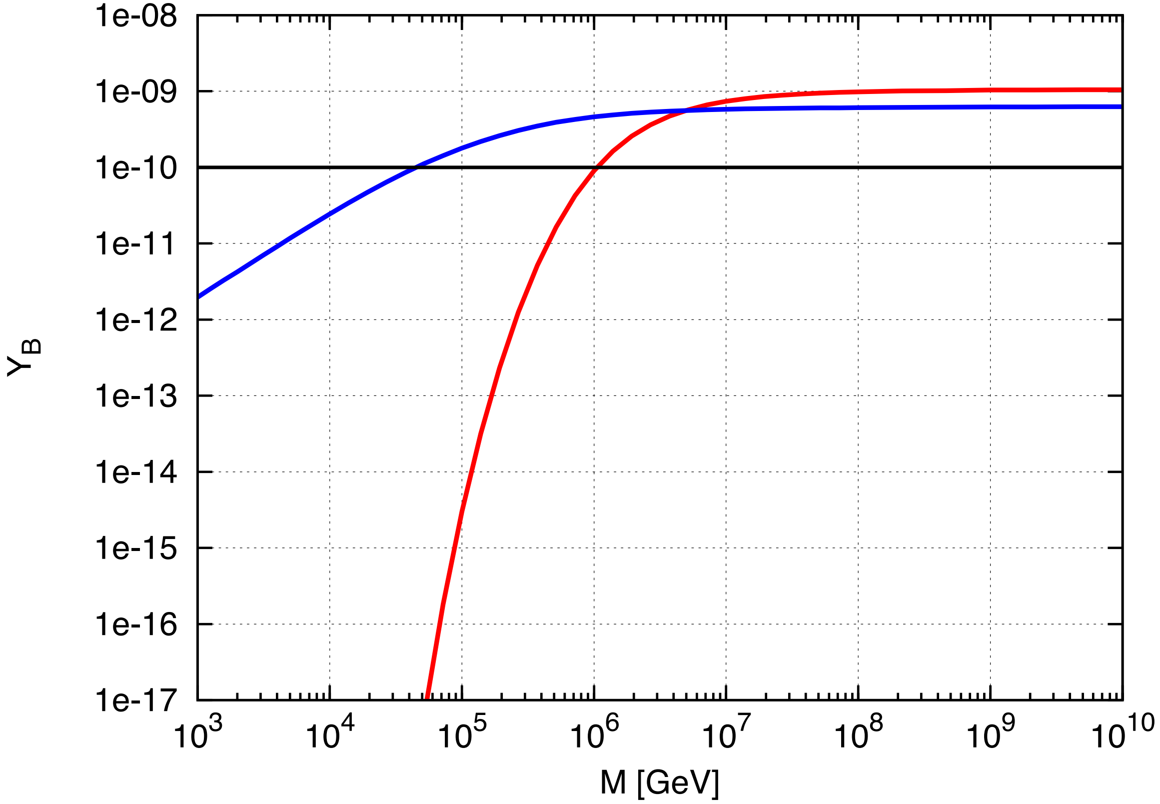
if $M_2 >> M_1$

washouts $\propto \left(\frac{\lambda_{\alpha 2}^2}{M_2}\right)^2$


N_1
H_2
ℓ
N_1
$\bar{\ell}$
N_2
H_2
$\bar{H}_2$
ℓ
N_1
$\bar{\ell}$
H_2
N_2
$\bar{H}_2$
ℓ
$\bar{\ell}$
N_2
H_2
$\bar{H}_2$
ℓ
$\bar{\ell}$
H_2
N_2
$\bar{H}_2$
ℓ

━━━━ without washouts ━━━━ with washouts

$$H_2\ell \leftrightarrow \overline{H}_2\bar{\ell}, \qquad \ell\ell \leftrightarrow \overline{H}_2\overline{H}_2$$



$$\frac{\Gamma_N}{H(T=M_N)} = const.$$

$$\epsilon_{CP} = const.$$

J. Racker, 2014

Ways out:

- Late decay: new interactions needed to produce N_1

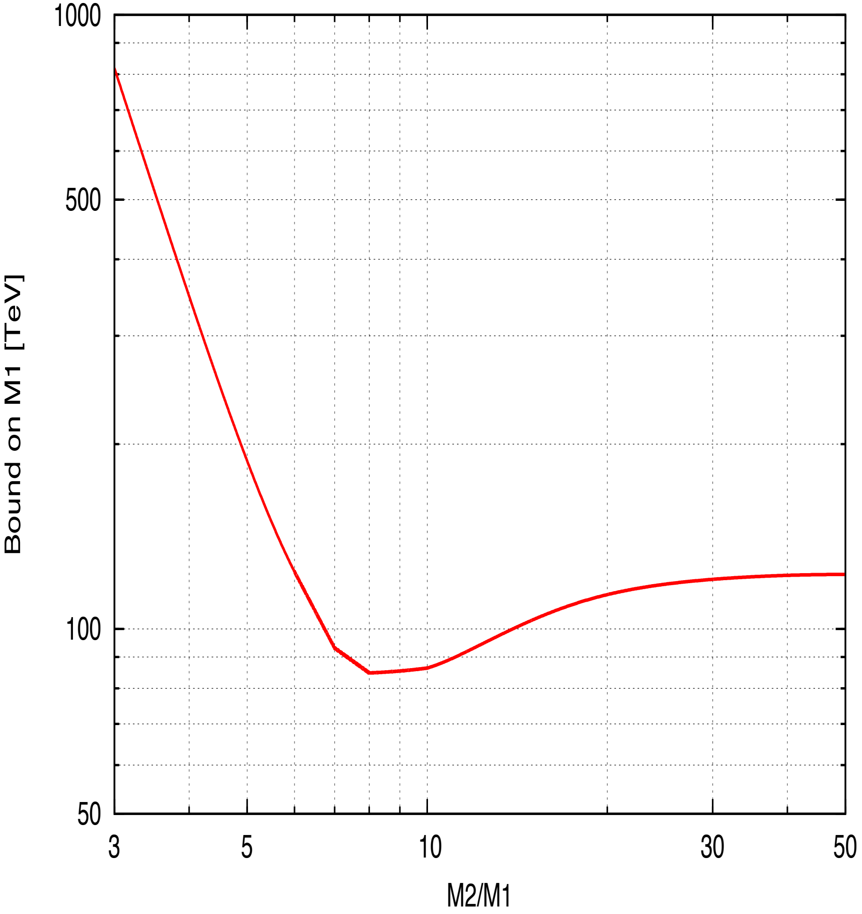
  [Plumacher 1997; Racker, Roulet 2009, Cui,Sundrum 2012]

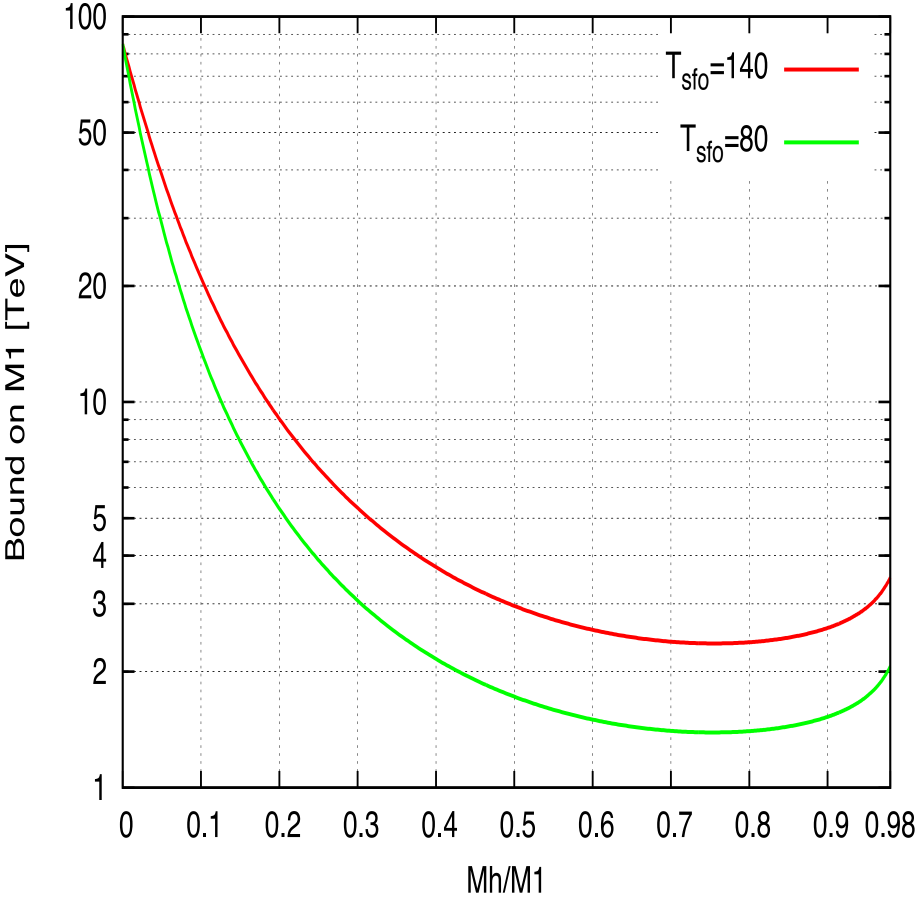
- Resonant leptogenesis

- Massive decay products:

  [Cui,Randall,Shuve, 2012; J. Racker, 2014]

Example: inert doublet


1000
500
100
50
Bound on M1 [TeV]
3
5
10
30
50
M2/M1


100
50
20
10
5
4
3
2
1
Bound on M1 [TeV]
T_{sfo}=140
T_{sfo}=80
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.98
Mh/M1

IV. Leptogenesis and DM

Baryonic Matter: asymmetric

Baryon mass: m_B = 938 MeV

Baryonic matter density:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \frac{n_B}{n_\gamma} \approx 6 \times 10^{-10}$$

Baryonic energy density:

Ω_B = 0.0463

Dark Matter

DM mass: m_{DM} = ?

DM density:

n_{DM} = ?

DM energy density:

Ω_{DM} = 0.233

$$\frac{\Omega_{DM}}{\Omega_B} \approx 5$$

WMAP, PLANCK,BBN

hint of a common origin ?

Asymmetric Dark Matter

DM mass: $m_{DM} \approx 5$ GeV

DM density:

$$n_{DM} = n_X - n_{\bar{X}} \approx n_B - n_{\bar{B}}$$

WIMP miracle is lost

WIMP Dark Matter

DM mass: $m_{DM} = 10\text{–}1000$ GeV

DM density: from thermal freezeout of weak interactions

WIMP miracle

BARYOGENESIS VIA WIMPs

Baryonic Matter

Baryonic matter density:

Generated by a decaying WIMP or in baryon and CP violating annihilations of the DM

Large CP asymmetry ε

WIMP Dark Matter

DM mass: $m_{DM} \approx 100\text{-}1000$ GeV

DM density: : from thermal freezeout of weak interactions (WIMP miracle)

McDonald 2011;Cui,Randall,Shuve; Davidson,Elmer; Cui,Sundrum 2012; Bernal et al. 2013; J. Racker, N.R., 2014

A) Baryogenesis in WIMP decay

There are at least two WIMPs :

χ : stable → DM

χ_B : unstable, with CP and B (or L) violating decays

BAU generated in the late-decay of a meta-stable WIMP after its thermal freeze-out [Cui,Sundrum 2012]

BAU generated in the decay of a pair of quasi-degenerate fermions whose density is determined by the freeze out of WIMP-like annihilations [Davidson Elmer 2012]

- The B-asymmetry inherits the would-be miracle abundance from the WIMP parent (up to a suppression factor ε_{CP})

$$\frac{\Omega_B}{\Omega_{DM}} = \epsilon_{CP} \frac{m_P}{M_{\chi_B}} \frac{\Omega_{\chi_B}^{\tau\to\infty}}{\Omega_{DM}}$$

- May be probed by displaced vertices at LHC
  [Cui, Shuve, 2015]

B) Baryogenesis from DM annihilation: WIMPy baryogenesis

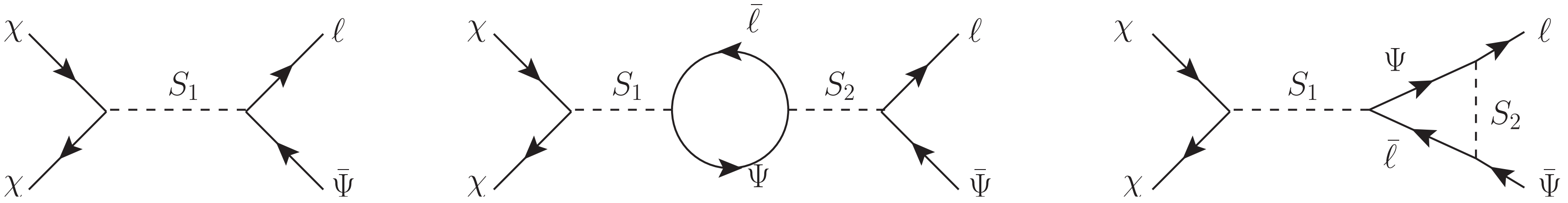
During the annihilation of WIMP-like DM, χ ,the Sakharov's conditions may be satisfied

[Cui,Randall,Shuve 2012; Bernal et al. 2013; Racker, NR, 2014]

Minimal content: fermionic DM, χ , at least two scalars S_1,S_2 and a heavy fermion ψ

$$\mathcal{L} = \mathcal{L}_{mass} + \mathcal{L}_{kin} - \frac{1}{2}\lambda_{\chi a}\bar{\chi}\chi S_a + \lambda_{Lai} S_a L_i \Psi_i + \text{h.c.}$$

$$\chi\chi \to L\Psi, \bar{L}\bar{\Psi}(Q\Psi, \bar{Q}\bar{\Psi})$$



$$\epsilon_{CP} = \frac{\gamma(\chi\chi \to L_i\Psi_i) - \gamma(\chi\chi \to \bar{L}_i\bar{\Psi}_i)}{\gamma(\chi\chi \to L_i\Psi_i) + \gamma(\chi\chi \to \bar{L}_i\bar{\Psi}_i)}$$

$$\frac{dY_\chi}{dz} = -\frac{2s(x)}{xH(x)}\langle\sigma_{ann}v\rangle\left[Y_\chi^2 - (Y_\chi^{eq})^2\right]$$

$$\frac{dY_{\Delta L}}{dz} \sim \epsilon_{CP}\frac{dY_\chi}{dz} - Y_{\Delta L}\left[\frac{\gamma(L\Psi \to \bar{L}\bar{\Psi})}{n_L^{eq}H}\right] - Y_{\Delta\Psi}\left[\frac{\gamma(L\Psi \to \bar{L}\bar{\Psi})}{n_\Psi^{eq}H}\right] + \ldots$$

$$Y_X \equiv n_X/s \;, \qquad z \equiv M_\chi/T$$

Successful WIMPy leptogenesis: correct BAU and WIMP relic density

- M_χ, M_{sa}, $M_\psi \approx$ (1-10) TeV
- $M_\chi < M_{sa}$
- $M_\chi < M_\psi < 2\, M_\chi$
- λ_L, $\lambda_X \approx O(1)$

- Possible connection to neutrino masses: WIMPy leptogenesis with sterile neutrinos [J. Racker talk]

MINIMAL LEPTOGENESIS AND DM: νMSM

Asaka, Shaposhnikov, 2005; Canetti et al. 2012

- Low scale (below EW) seesaw scenario: SM + three singlet Majorana fermions
- DM candidate: lightest neutral lepton, M_{DM} O(10) keV
- Leptogenesis via sterile neutrino oscillations

V. Leptogenesis via sterile neutrino oscillations

Akhmedov, Rubakov, Smirnov, 1998

- Density matrix formalism , starting point: Raffelt-Sigl formulation of kinetic equations

$$\dot{\rho} = -i[H,\rho] - \frac{1}{2}\{\Gamma, \rho - \rho^{eq}\}$$

- Analytical approximate solutions
- ARS: 3 sterile neutrinos ➔ no mass degeneracy, $M_N \approx O(10)$ GeV, standard seesaw neutrino Yukawa couplings , $Y_{1,2} \approx 10^{-6}$, $Y_3 \ll Y_{1,2}$

- δ_{CP} depends on Jarlskog invariant of sterile neutrino mixing matrix

- 2 sterile neutrino oscillations + SM lepton flavour:

$$(\delta_{CP})_\alpha \propto \sum_{j\neq i} \mathrm{Im}[\lambda^*_{\alpha j}\lambda_{\alpha i}(\lambda^\dagger\lambda)_{ij}]\, g(M_i, M_j)$$

(same as in $\epsilon^L_{\alpha i}$ from heavy neutrino decay)

- strong mass degeneracy and/or tuning of Yukawa couplings [inverse seesaw limit]

Shuve, Yavin, 2014; Canetti et al. 2014

- 3 sterile neutrino oscillations + SM lepton flavour:
  - Non equilibrium QFT calculation of flavoured CP asymmetries, $(\delta_{CP})_\alpha$ ➔ leptogenesis viable for GeV sterile neutrinos, without mass degeneracy

    Drewes, Garbrecht, 2012; Canetti et al., 2015

  - Density matrix formalism: approximate analytic solution expanding in mixing angles + exact numerical solution [M. Kekic poster and talk]

    Hernández, Kekic, López-Pavón, Racker, NR, in preparation

VI. And the LHC/0νββ ?

- Leptogenesis in type 1 seesaw very hard to test: either very high sterile neutrino masses or tiny Yukawa couplings, except in the inverse seesaw limit: resonant leptogenesis, GeV scale sterile neutrinos at LHCb/BELLE II, SHIP [Canetti et al., 2015] and W, Higgs decays with displaced vertices [Helo et al. 2014, Gago et al., 2015]

- Possible hints in ISS and other scenarios:
  - charged lepton flavour violation and EDMs

- Observation of QCD sphalerons in heavy ion collisions at LHC [Kharzeev, McLerran, Warringa, 2008]

- EW sphalerons at LHC ? arXiv:1505.03690

- Easier to falsify high scale leptogenesis:

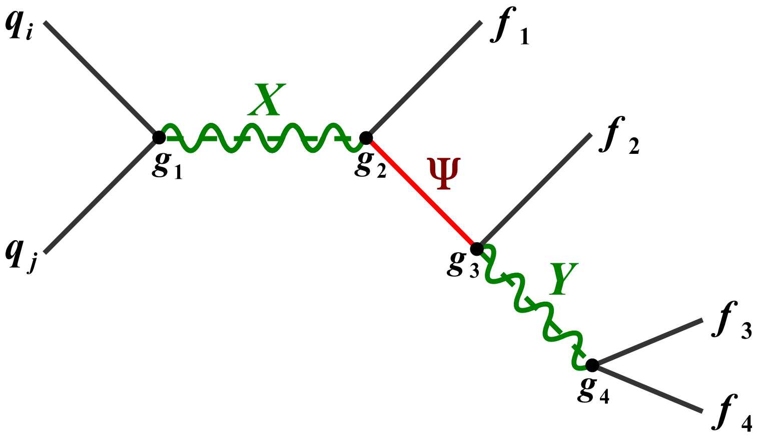
- Discovery of a W_R coupling to a N and a RH lepton

at LHC will disfavour leptogenesis in N decay [Frère, Hambye, Vertongen, 2009], allowing only particular textures [Dev, Lee, Mohapatra, 2014]

- LNV observed at LHC will also disfavour high scale leptogenesis [Deppisch, Harz, Hirsch 2014]:

  same sign dileptons via resonant processes

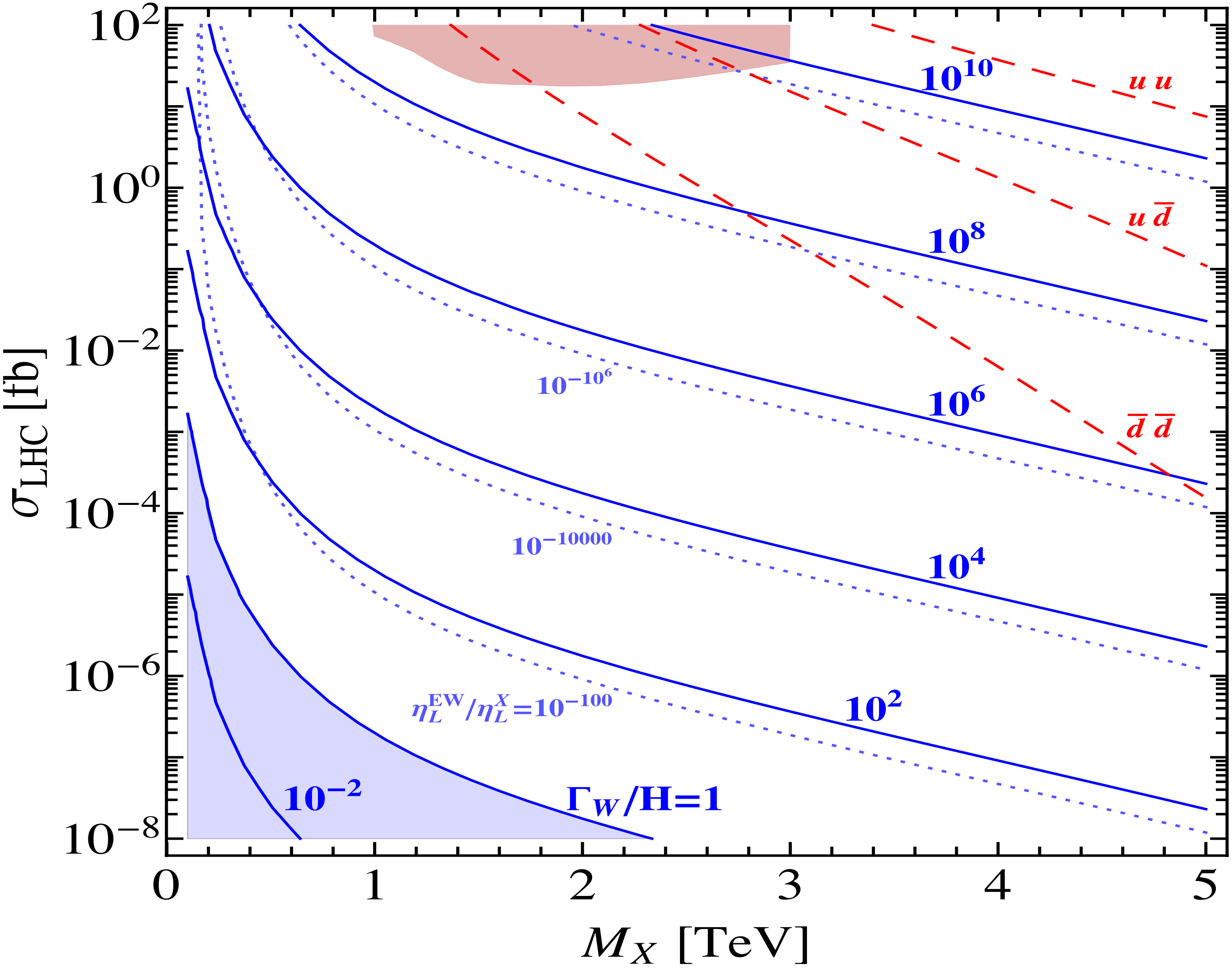
$$pp \to \ell^{\pm}\ell^{\pm}qq$$



X will induce a washout of the lepton number asymmetry, via $qq \to \ell^\pm \ell^\pm qq$, given by:

$$\frac{\Gamma_W}{H} = \frac{0.028}{\sqrt{g_*}} \frac{M_P M_X^3}{T^4} \frac{K_1(M_X/T)}{f_{q_1,q_2}(M_X/\sqrt{s})} \times (s\sigma_{LHC})$$

→ pdf's


$\sigma_{\rm LHC}$ [fb]
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
0
1
2
3
4
5
M_X [TeV]
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{-2}
$\Gamma_W/H=1$
$u\,u$
$u\,\bar{d}$
$\bar{d}\,\bar{d}$
10^{-10^6}
10^{-10000}
$\eta_L^{\rm EW}/\eta_L^X=10^{-100}$

- Note: to falsify leptogenesis, one has to make sure that lepton flavour violating interactions are also in equilibrium:

- Otherwise, a lepton asymmetry may survive in the tau flavour, even if LNV in e,μ channels is observed

Effective operator approach for 0νββ decay and CLFV:

Deppisch et al. 2015

$$\mathcal{O}_5 = (L^i L^j) H^k H^l \epsilon_{ik}\epsilon_{jl}$$

$$\mathcal{O}_7 = (L^i d^c)(\overline{e^c}\,\overline{u^c}) H^j \epsilon_{ij}$$

$$\mathcal{O}_9 = (L^i L^j)(\bar{Q}_i \overline{u^c})(\bar{Q}_j \overline{u^c})$$

$$\mathcal{O}_{11} = (L^i L^j)(Q_k d^c)(Q_l d^c) H^m \bar{H}_i \epsilon_{jk}\epsilon_{lm}$$

Single operator dominance:

$$T_{1/2} = 2.1 \times 10^{25} y \, (\Lambda_D/\Lambda_D^0)^{2d-8}$$

and rate of $\Delta L = 2$ processes:

$$\frac{\Gamma_W}{H} = \frac{c_d}{n_\gamma H} \frac{T^{2d-4}}{\Lambda_d^{2d-8}} \approx 0.3\, c_d \frac{M_P}{\Lambda_d} \left(\frac{T}{\Lambda_d}\right)^{2d-9}$$

- $\Gamma_W/H > 1$ ➔ $\Delta L = 2$ processes in equilibrium and effective washout of the lepton asymmetry
- LFV operators:

$$\mathcal{O}_{\ell\ell\gamma} = \mathcal{C}_{\ell\ell\gamma} \bar{L}_\ell \sigma^{\mu\nu} \bar{\ell}^c H F_{\mu\nu}$$

$$\mathcal{O}_{\ell\ell qq} = \mathcal{C}_{\ell\ell qq} (\bar{\ell} \Pi_1 \ell)(\bar{q} \Pi_2 q)$$

$$\mathcal{C}_{\ell\ell\gamma} \sim \frac{e}{16\pi^2 \Lambda^2_{\ell\ell\gamma}} \,, \qquad \mathcal{C}_{\ell\ell qq} \sim \frac{1}{\Lambda^2_{\ell\ell qq}}$$

- With these, one obtains:

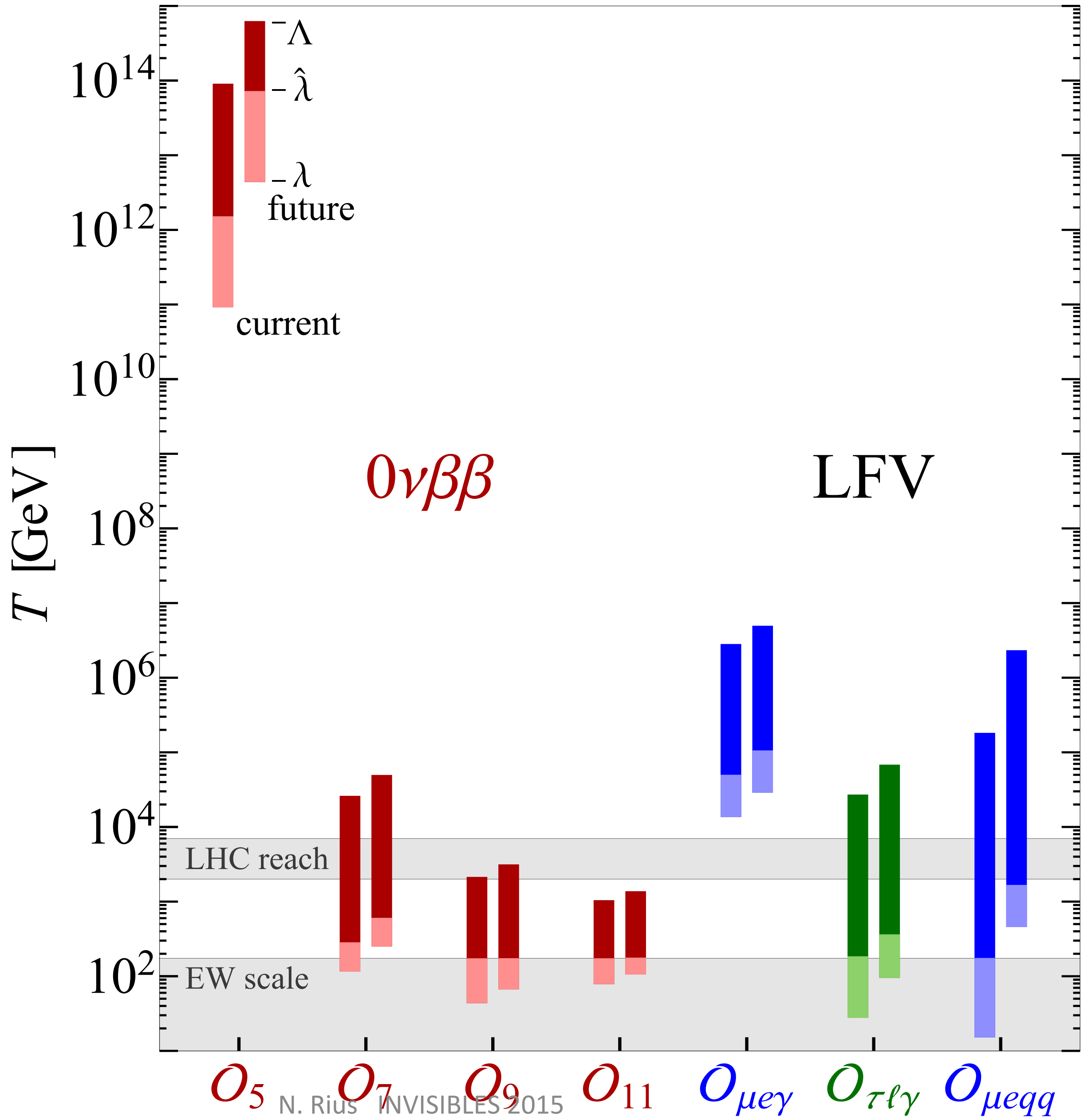
$$BR(\mu \to e\gamma) = 5.7 \times 10^{-13} \, (\Lambda^0_{\mu e\gamma}/\Lambda_{\mu e\gamma})^4$$

- LFV in equilibrium ➔ individual flavour number asymmetries equilibrated by LFV $\Delta L = 0$ processes

$$\frac{\Gamma_W}{H} \gtrsim 1$$

for

$$T > \lambda$$



VII. Summary and outlook

- Thermal leptogenesis in type I seesaw: simple, appealing … but difficult to test [except ISS limit]

- WIMP baryogenesis: relates Ω_B and Ω_{DM}, keeping the WIMP miracle

- Progress understanding sterile neutrino oscillations, still work to do

- LNV@LHC and/or $0\nu\beta\beta$ decay may falsify high scale leptogenesis scenarios

- Maximal resonant enhancement:

$$R_{max} = \frac{M_1 M_2}{2|M_1\Gamma_1 - M_2\Gamma_2|}$$

Covi, Roulet, 1997; Anisimov et al., 2006

- Non-equilibrium QFT calculation (Kadanoff-Baym eqs.), and Pilaftsis computation:

$$R_{max}^{KB,P} = \frac{M_1 M_2}{2(M_1\Gamma_1 + M_2\Gamma_2)}$$