Neutrino masses and the matter-antimatter asymmetry of the Universe

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- the observational evidence for a baryon asymmetry
- necessity of a dynamical generation mechanism
- electroweak baryogenesis in the Standard Model
- a link with neutrino masses: baryogenesis via leptogenesis
- leptogenesis and Grand Unification
- a predictive scheme for (triplet) leptogenesis
- Conclusions

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Introduction

The Standard Model of strong and electroweak interactions is one of the most successful theories in physics, and the new boson discovered by the LHC could be its last missing piece: the Higgs boson

Nevertheless the Standard Model fails to account for several observational facts, most notably dark matter, dark energy and the baryon asymmetry (or matter-antimatter asymmetry) of the Universe

Both dark matter and the BAU require an extension of the Standard Model, which depending on its nature may or may not lead to an observable signal at the LHC or in other experiments

Neutrino masses (evidenced by the numerous observations of neutrino oscillations) also call for new physics beyond the Standard Model, and may have a common origin with the BAU, thanks to a mechanism known as leptogenesis

The observational evidence

How do we know that there is (almost) no antimatter in the Universe?

Mere observation: the structures we observe in the Universe are made of matter (p, n, e-). No significant presence of antimatter (anti-p, anti-n, e+):

* solar system: no presence of antimatter

* milky way: $\bar{p}/p \approx 10^{-4}$ in cosmic rays - fully understood in terms of

$$p\,(\mathrm{primary\,CR}) + p\,(\mathrm{interstellar\,gas}) \rightarrow 3p + \bar{p}$$

* clusters of galaxies: would observe strong γ-ray emission from matter-antimatter annihilations, such as $p + \bar{p} \rightarrow \pi^0 + X \rightarrow \gamma\gamma + X$

Could there be matter/antimatter separation over larger scales?

Would require violation of causality (the causal horizon before annihilation freeze-out contained only a tiny fraction of our visible Universe)

The matter-antimatter asymmetry of the Universe is measured by the baryon-to-photon ratio:

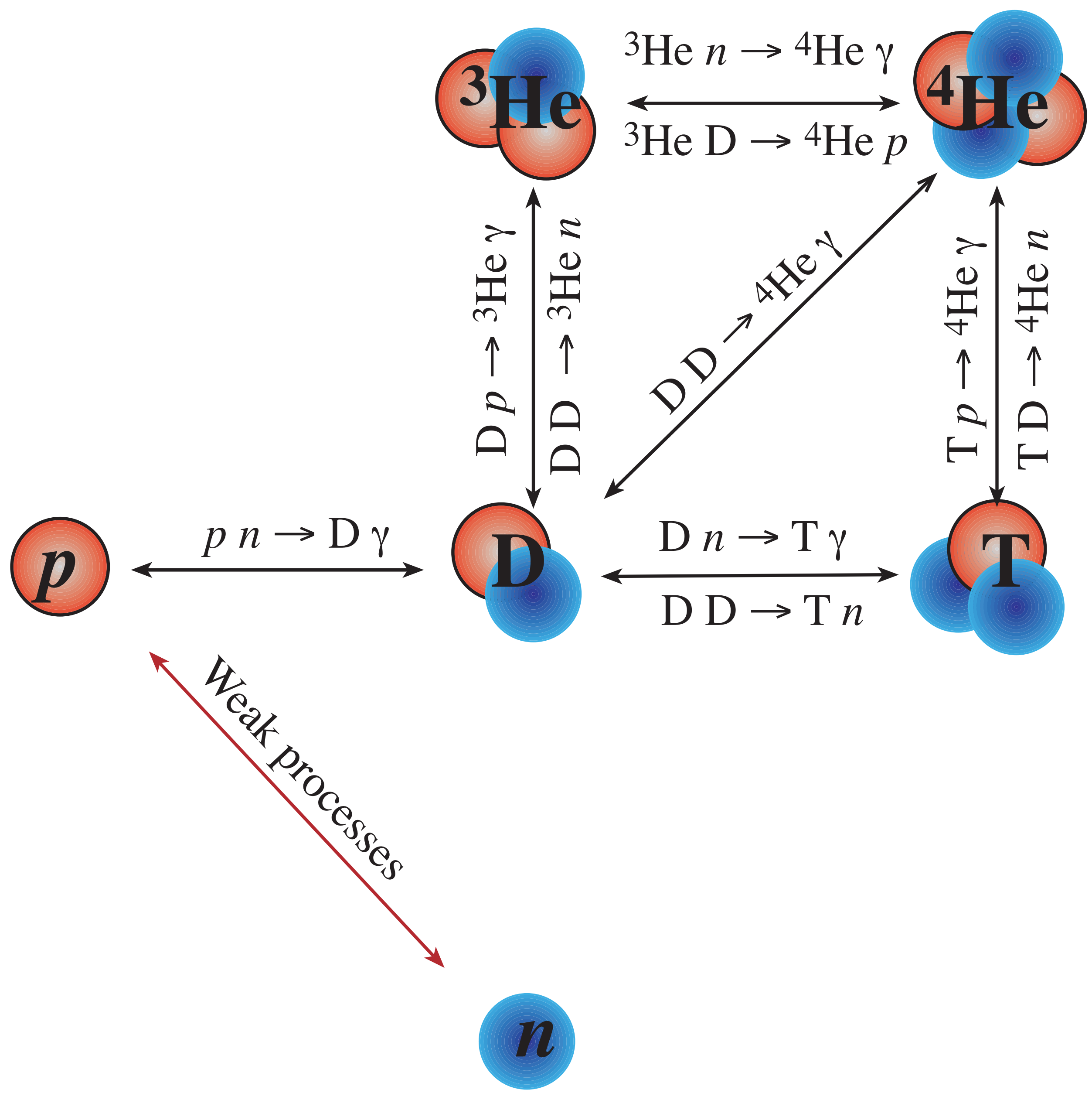
$$\eta \equiv \frac{n_B}{n_\gamma} \simeq \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

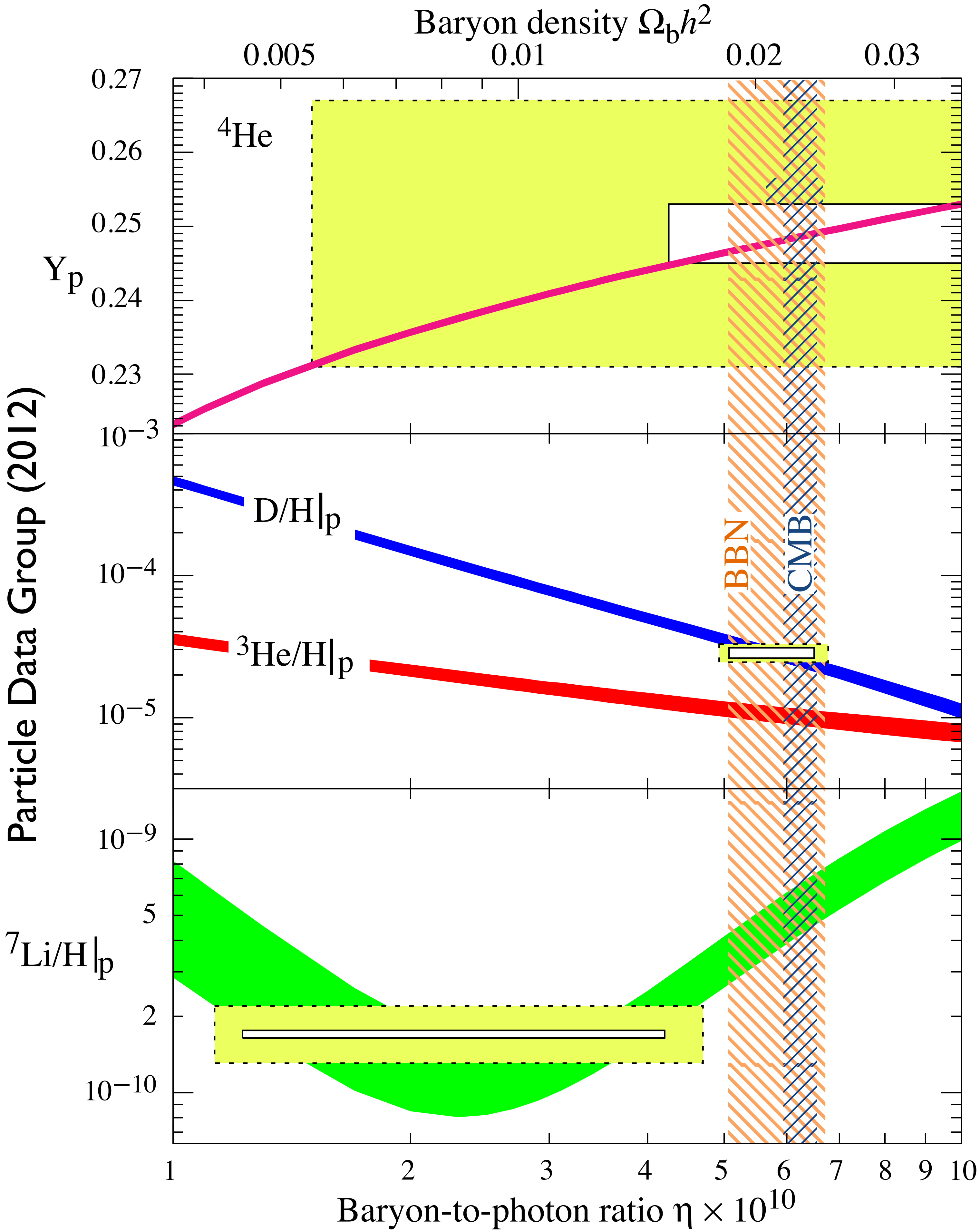
2 independent determinations of Y_B:

(i) light element abundances

(ii) anisotropies of the cosmic microwave background (CMB)

Big Bang nucleosynthesis predicts the abundances of the light elements (D, ^{3}He, ^{4}He and ^{7}Li) as a function of η

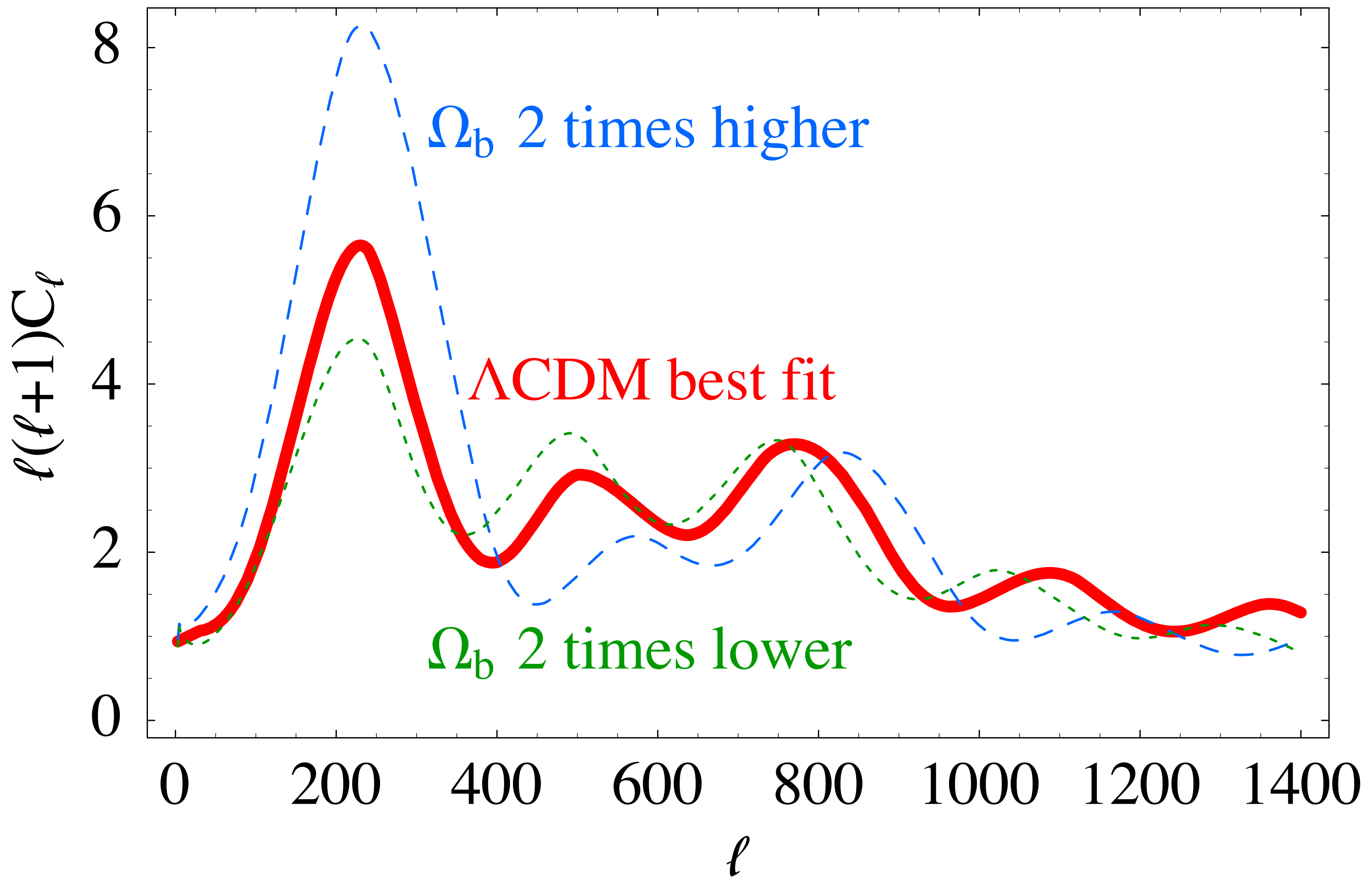




The fact that there is a range of values for η consistent with all observed abundances ("concordance") is a major success of Big Bang cosmology

$$\eta = (5.1 - 6.5) \times 10^{-10}$$

- bands = 95% C.L.
- smaller boxes = ±2σ statistics
- larger boxes = ±2σ statistics and systematics



A. Strumia, hep-ph/0608347

Information on the cosmological parameters can be extracted from the temperature anisotropies of the CMB

In particular, the anisotropies are affected by the oscillations of the baryon-photon plasma before recombination, which depend on η (or $\Omega_b h^2$)

$$\Rightarrow \quad \eta = (6.04 \pm 0.08) \times 10^{-10} \quad \text{(Planck)}$$

$\Rightarrow$ remarkable agreement between the CMB and BBN determinations of the baryon asymmetry: another success of standard Big Bang cosmology

$$\eta = (5.1 - 6.5) \times 10^{-10} \qquad \text{(BBN)}$$

$$\eta = (6.04 \pm 0.08) \times 10^{-10} \qquad \text{(Planck)}$$

Although this number might seem small, it is actually very large:

in a baryon-antibaryon symmetric Universe, annihilations would leave a relic abundance

$$n_B/n_\gamma = n_{\bar{B}}/n_\gamma \approx 5 \times 10^{-19}$$

The necessity of a dynamical generation

In a baryon-antibaryon symmetric Universe, annihilations would leave a relic abundance $n_B/n_\gamma = n_{\bar{B}}/n_\gamma \approx 5 \times 10^{-19}$

Since at high temperatures $n_q \sim n_{\bar{q}} \sim n_\gamma$, one would need to fine-tune the initial conditions in order to obtain the observed baryon asymmetry as a result of a small primordial excess of quarks over antiquarks:

$$\frac{n_q - n_{\bar{q}}}{n_q} \approx 3 \times 10^{-8}$$

Furthermore, our Universe most probably underwent a phase of inflation, which exponentially diluted the initial conditions

$\Rightarrow$ need a mechanism to dynamically generate the baryon asymmetry

Baryogenesis!

Conditions for baryogenesis

Sakharov's conditions [1967]:

(i) Baryon number (B) violation

(ii) C and CP violation

If C were conserved, any processes creating n baryons would occur at the same rate as the C-conjugated process creating n antibaryons, resulting in a vanishing net baryon asymmetry

CP violation is also needed, otherwise the processes creating baryons and the CP-conjugated processes creating antibaryons would balance each other once integrated over phase space

(iii) departure from thermal equilibrium

otherwise the baryons created by some process would be destroyed by the inverse process, resulting in a vanishing net baryon asymmetry

Quite remarkably, the Standard Model (SM) of particle physics satisfies all three Sakharov's conditions:

(i) B is violated by non-perturbative processes known as sphalerons

(ii) C and CP are violated by weak interactions (CP violation due to the CKM phase)

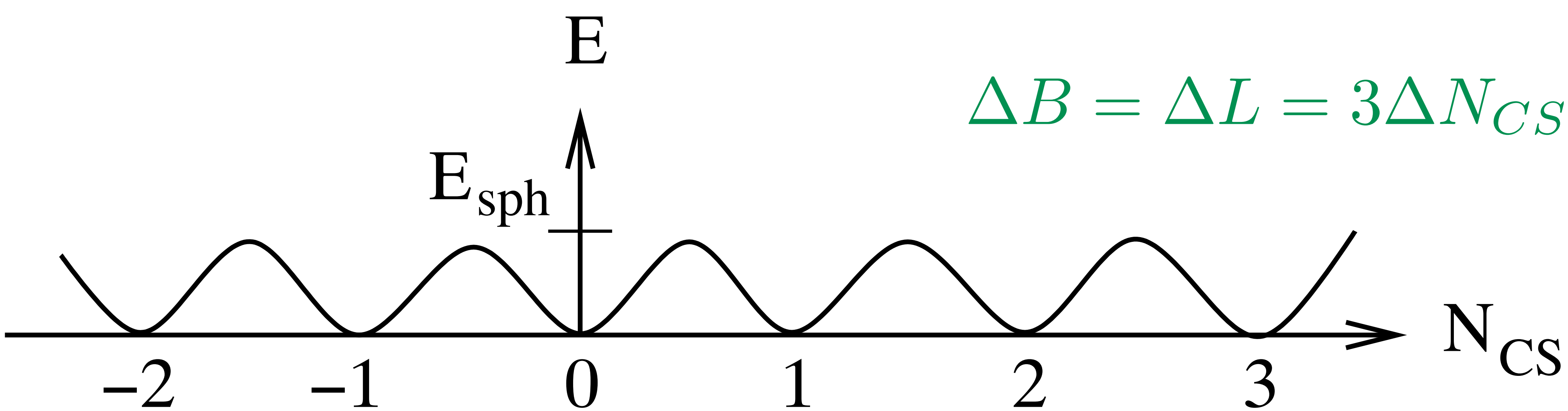
(iii) departure from thermal equilibrium can occur during the electroweak phase transition

→ ingredients of electroweak baryogenesis

Baryon number violation in the Standard Model

The baryon (B) and lepton (L) numbers are accidental global symmetries of the SM Lagrangian $\Rightarrow$ all perturbative processes preserve B and L

However, B+L is violated at the quantum level (anomaly)
$\Rightarrow$ non-perturbative transitions between vacua of the electroweak theory characterized by different values of B+L [but B-L is conserved]



$$\Delta B = \Delta L = 3\Delta N_{CS}$$

At T=0, transitions by tunneling: $\Gamma(T=0) \sim e^{-16\pi^2/g^2} \sim 10^{-150}$ ['t Hooft]

$\Rightarrow$ extremely suppressed: no baryogenesis?

However, this is different at finite temperature

- above the electroweak phase transition [$T > T_{EW} \sim 100\,\mathrm{GeV}$], i.e. in the unbroken phase [$\langle\phi\rangle = 0$], (B+L) violation is unsuppressed:

$$\Gamma(T > T_{EW}) \;\sim\; \alpha_W^5 T^4 \qquad\qquad \alpha_W \equiv g^2/4\pi$$

[Kuzmin, Rubakov, Shaposhnikov]

- below the electroweak transition [$0 < T < T_{EW}\,, \langle\phi\rangle \neq 0$]:

$$\Gamma(T < T_{EW}) \;\propto\; e^{-E_{sph}(T)/T}$$

[Arnold, McLerran - Khlebnikov, Shaposhnikov]

where E_{sph} (T) is the energy of the gauge field configuration ("sphaleron") that interpolates between two vacua [Klinkhamer, Manton]

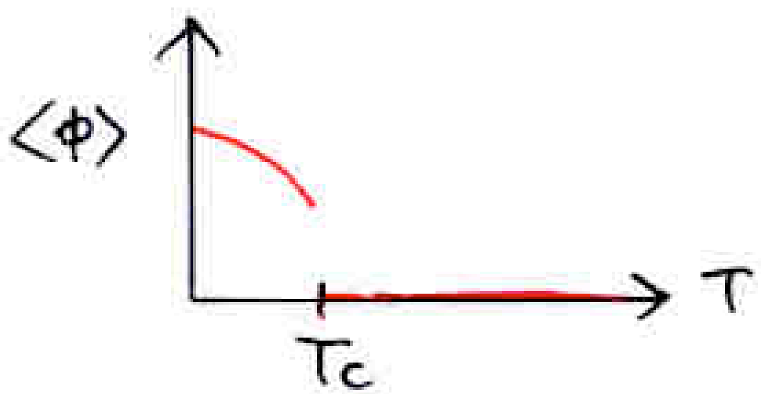
$\Longrightarrow$ electroweak baryogenesis [=baryogenesis at the electroweak phase transition] becomes possible

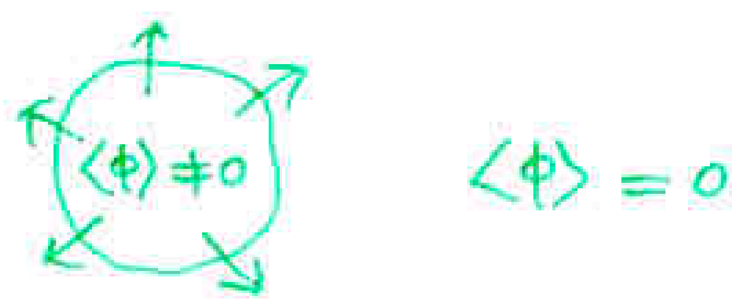
Baryogenesis in the Standard Model: rise and fall of electroweak baryogenesis

The order parameter of the electroweak phase transition is the Higgs vev:

- $T > T_{EW}, \langle\phi\rangle = 0$ unbroken phase
- $T < T_{EW}, \langle\phi\rangle \neq 0$ broken phase

If the phase transition is first order, the two phases coexist at $T = T_c$ and the phase transition proceeds via bubble nucleation





[Cohen, Kaplan, Nelson]

Sphalerons are in equilibrium outside the bubbles, and out of equilibrium inside the bubbles (rate exponentially suppressed by $E_{sph}(T) / T$)

CP-violating interactions in the wall together with unsuppressed sphalerons outside the bubble generate a B asymmetry which diffuses into the bubble

For the mechanism to work, it is crucial that sphalerons are suppressed inside the bubbles (otherwise will erase the generated B+L asymmetry)

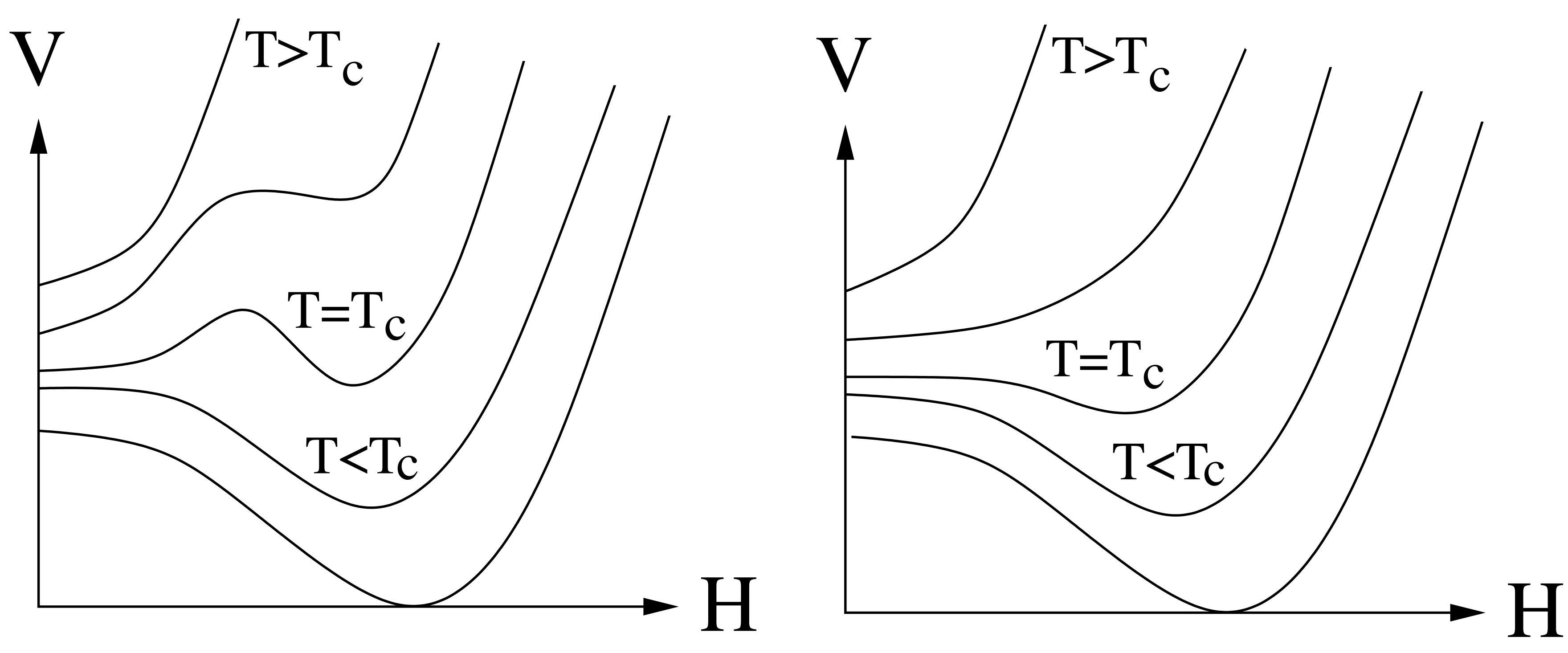
$$\Gamma(T < T_{EW}) \;\propto\; e^{-E_{sph}(T)/T} \quad \text{with} \quad E_{sph}(T) \;\approx\; (8\pi/g)\,\langle\phi(T)\rangle$$

The out-of-equilibrium condition is

$$\frac{\langle\phi(T_c)\rangle}{T_c} \gtrsim 1$$

→ strongly first order phase transition required!

To determine whether this is indeed the case, need to study the 1-loop effective potential at finite temperature



The thermally generated cubic term induces a first order transition, with two degenerate minima at the critical temperature, $\Phi = 0$ and

$$\phi(T_c) \;=\; \frac{2ET_c}{\lambda(T_c)} \;\simeq\; \frac{4Ev^2T_c}{m_H^2}$$

The out-of-equilibrium condition $\Phi(T_c)/T_c > 1$ then translates into:

$m_H \lesssim 40\,\mathrm{GeV}$ condition for a strong first order transition

→ excluded by LEP. Actually it has been shown that for $m_H \gtrsim 75\,\mathrm{GeV}$ there is no phase transition but a smooth crossover [Arnold]

Also CP-violating effects are too small in the SM [Gavela, Hernandez, Orloff, Pène]

→ standard electroweak baryogenesis fails: the observed baryon asymmetry requires new physics beyond the Standard Model

The observed baryon asymmetry requires new physics beyond the Standard Model

→ 2 approaches:

1) modify the dynamics of the electroweak phase transition [+ new source of CP violation needed]

MSSM with a light top squark, 2 Higgs doublet model, non-standard electroweak symmetry breaking mechanism...

2) generate a B-L asymmetry at $T > T_{EW}$, which is then converted into a B asymmetry by sphaleron processes

out-of-equilibrium decays of heavy gauge bosons (= GUT baryogenesis, however conflict with inflation) or of heavy states coupling to the neutrinos (leptogenesis), Affleck-Dine mechanism...

A link with neutrino masses: Baryogenesis via leptogenesis

The observation of neutrino oscillations from different sources (solar, atmospheric and accelerator/reactor neutrinos) has led to a well-established picture in which neutrinos have tiny masses and can change flavour (e.g. $\nu_e \to \nu_\mu \,/\, \nu_\tau$) as they propagate

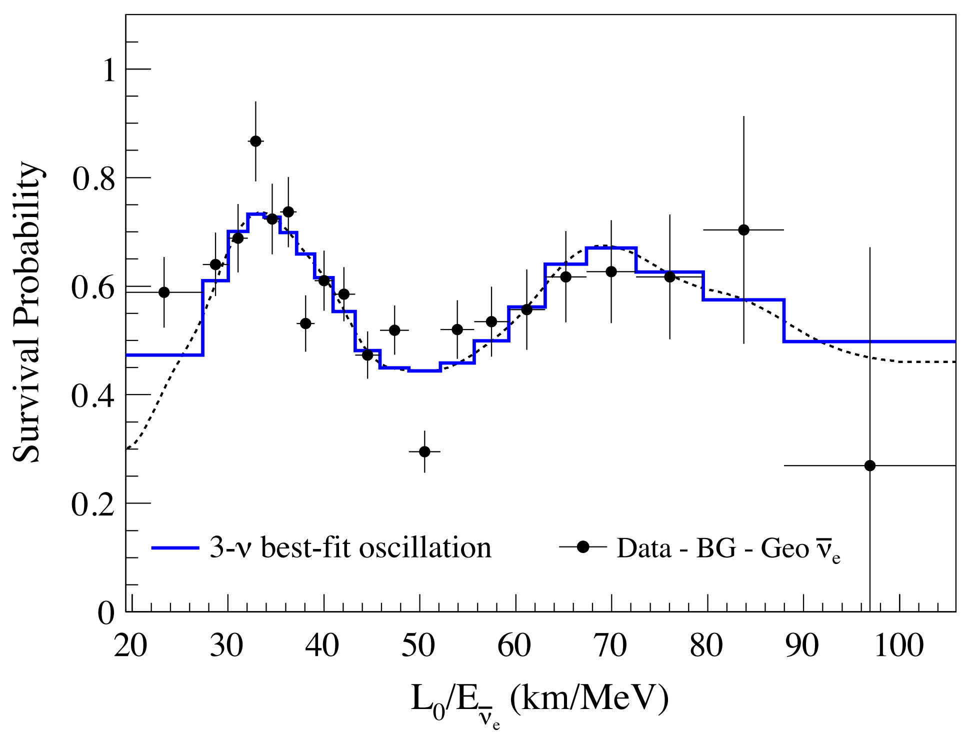


FIG. 5: Ratio of the observed $\overline{\nu}_e$ spectrum to the expectation for no-oscillation versus L_0/E for the KamLAND data. $L_0 = 180\,\mathrm{km}$ is the flux-weighted average reactor baseline. The 3-ν histogram is the best-fit survival probability curve from the three-flavor unbinned maximum-likelihood analysis using only the KamLAND data.

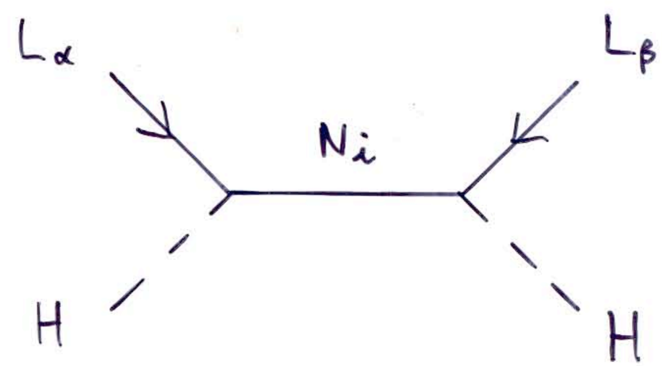
disparition of reactor $\overline{\nu}_e$ in the KamLAND experiment due to their oscillations into $\overline{\nu}_\mu$ and $\overline{\nu}_\tau$

$$P\left(\overline{\nu}_e \to \overline{\nu}_e\right) = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

The tiny neutrino masses can be interpreted in terms of a high scale:

$$m_\nu = \frac{v_{EW}^2}{M} \qquad M \sim 10^{14}\,\mathrm{GeV}$$

Several mechanisms can realize this mass suppression. The most popular one (type I seesaw mechanism) involves heavy Majorana neutrinos:



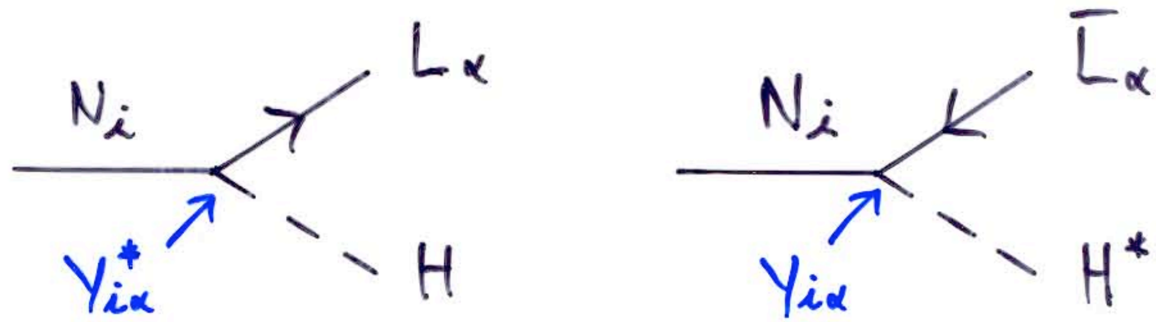
$$\Rightarrow \qquad m_\nu \sim \frac{y^2 v^2}{M_R}$$

Minkowski - Gell-Mann, Ramond, Slansky
Yanagida - Mohapatra, Senjanovic

Interestingly, this mechanism contains all required ingredient for baryogenesis: out-of-equilibrium decays of the heavy Majorana neutrinos can generate a lepton asymmetry (L violation replaces B violation and is due to the Majorana masses) if their couplings to SM leptons violate CP

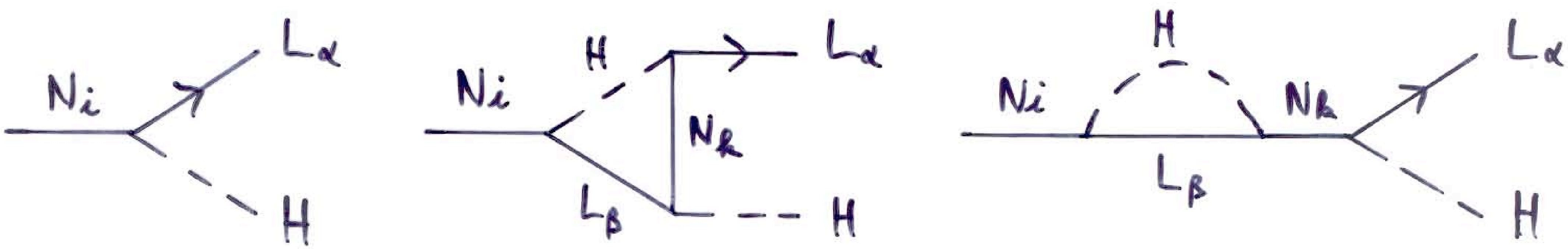
[Fukugita, Yanagida]

<u>CP violation</u>: being Majorana fermions, the heavy neutrinos are their own antiparticles and can decay both into l^+ and into l^-



$N_i \to L_\alpha H$ $\qquad$ $N_i \to \bar{L}_\alpha H^*$

The decay rates into l^+ and into l^- differ due to quantum corrections



$$\Longrightarrow \quad \Gamma(N_i \to LH) \neq \Gamma(N_i \to \bar{L}H^\star)$$

$\Longrightarrow$ asymmetry between lepton and antilepton abundances, which is partially washed out by L-violating processes and converted into a baryon asymmetry by the sphalerons

The final baryon asymmetry can be expressed as:

$$Y_B = -0.42\, C\, \frac{\eta\, \epsilon_{N_1}}{g_\star} = -1.4 \times 10^{-3}\, \eta\, \epsilon_{N_1} \quad \text{(SM)}$$

C = conversion factor by sphaleron

$$<Y_B>_T = C <Y_{B-L}>_T \qquad C = \frac{8N_f + 4N_H}{22N_f + 13N_H} = \frac{28}{79} \quad \text{(SM)}$$

g* = total number of relativistic dofs [g* = 106.75 in the SM]

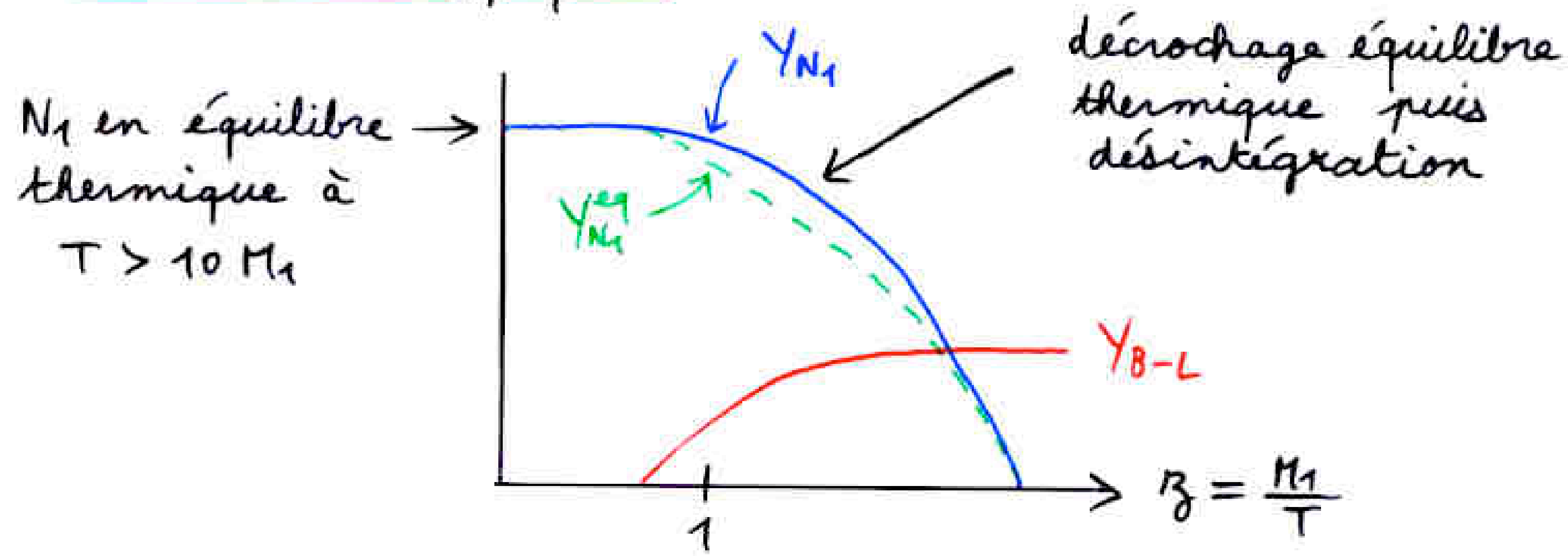
ϵ_{N_1} = CP asymmetry in N_1 decays

η = efficiency factor that takes into account the dilution of the lepton asymmetry by L-violating processes ($LH \to N_1,\ LH \leftrightharpoons \bar{L}H^\star \cdots$)

→ must be determined by solving Boltzmann equations

baryogenesis via leptogenesis

évolution typique:



Leptogenesis can explain the observed baryon asymmetry:

Case $M_1 \ll M_2, M_3$

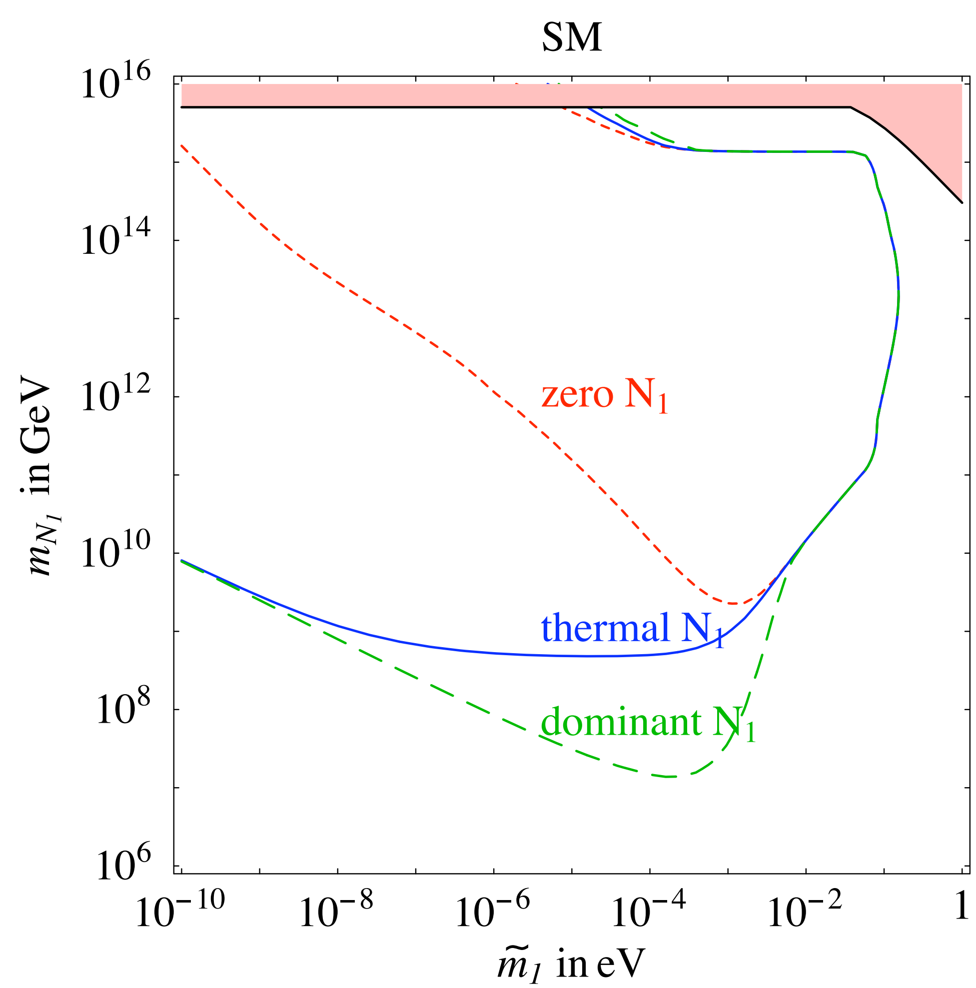
→ $M_1 \geq (0.5 - 2.5) \times 10^9\,\mathrm{GeV}$

depending on the initial conditions

[Davidson, Ibarra]

$M_1 \ll 10^9\,\mathrm{GeV}$ possible if $M_1 \simeq M_2$

("resonant leptogenesis") [Covi, Roulet, Vissani - Pilaftsis]



[Giudice et al., hep-ph/0310123]

Is leptogenesis related to low-energy (= PMNS) CP violation?

leptogenesis: $\epsilon_{N_1} \propto \sum_k \mathrm{Im}\,[(YY^\dagger)_{k1}]^2\, M_1/M_k$ depends on the phases of $YY^\dagger$

low-energy CP violation: phases of U_{PMNS} $\begin{cases} \delta & \to \text{oscillations} \\ \phi_2, \phi_3 & \to \text{neutrinoless double beta} \end{cases}$

→ are they related?

$$\underbrace{Y}_{\text{base où } M_e,\, M_R \text{ diag.}} = \underbrace{\begin{pmatrix} \sqrt{M_1} & & \\ & \sqrt{M_2} & \\ & & \sqrt{M_3} \end{pmatrix}}_{3 \text{ masses } N_R} R \underbrace{\begin{pmatrix} \sqrt{m_1} & & \\ & \sqrt{m_2} & \\ & & \sqrt{m_3} \end{pmatrix} U^+}_{9 \text{ paramètres basse énergie}}$$

(Casas, Ibarra)

R complexe, $R^T R = \mathbb{1}$ $\Rightarrow$ 3 param. complexes

→ leptogénèse: $YY^+ = \begin{pmatrix} \sqrt{M_1} & & \\ & \sqrt{M_2} & \\ & & \sqrt{M_3} \end{pmatrix} R \begin{pmatrix} m_1 & & \\ & m_2 & \\ & & m_3 \end{pmatrix} R^+ \begin{pmatrix} \sqrt{M_1} & & \\ & \sqrt{M_2} & \\ & & \sqrt{M_3} \end{pmatrix}$

→ leptogenesis only depends on the phases of R = high-energy phases

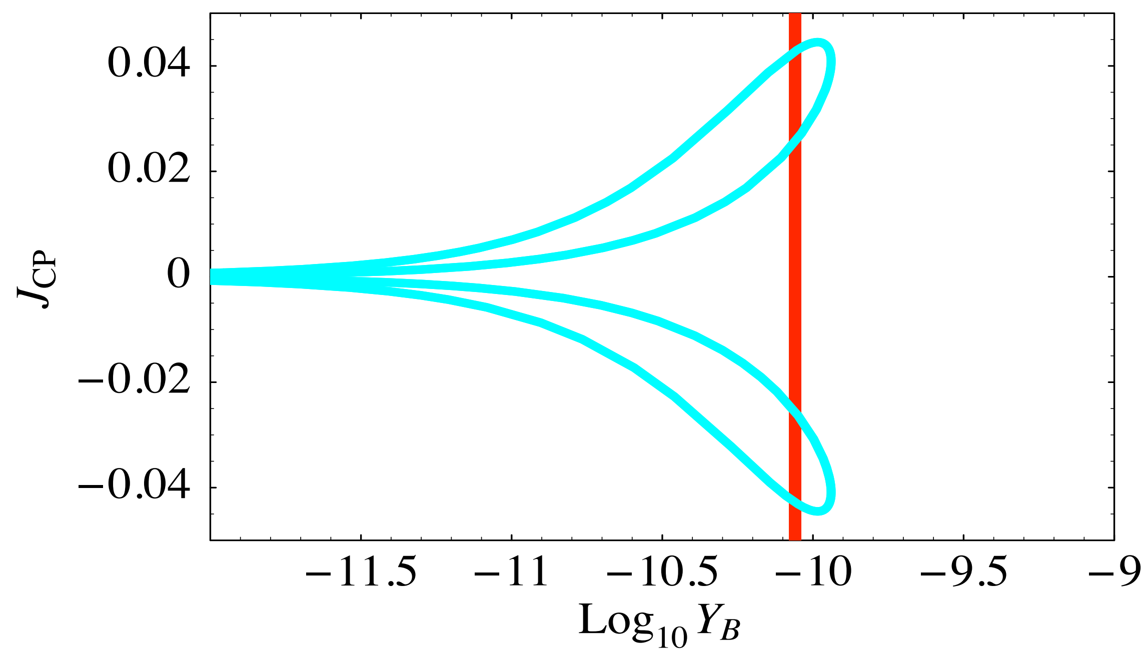
⇒ unrelated to CP violation at low-energy, except in ad hoc scenarios

However, if lepton flavour effects play an important role, the high-energy and low-energy phases both contribute to the CP asymmetry and cannot be disentangled. Leptogenesis possible even if all high-energy phases (R) vanish

Asymmetry in the flavour lα:

$$\epsilon_\alpha = -\frac{3M_1}{16\pi v^2}\frac{\mathrm{Im}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\alpha\beta} U_{\alpha\rho} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2}$$

leptogenesis from PMNS phase δ



[Pascoli, Petcov, Riotto]

FIG. 1. The invariant $J_{\rm CP}$ versus the baryon asymmetry varying (in blue) $\delta = [0, 2\pi]$ in the case of hierarchical RH neutrinos and NH light neutrino mass spectrum for $s_{13} = 0.2$, $\alpha_{32} = 0$, $R_{12} = 0.86$, $R_{13} = 0.5$ and $M_1 = 5 \times 10^{11}$ GeV . The red region denotes the 2σ range for the baryon asymmetry.

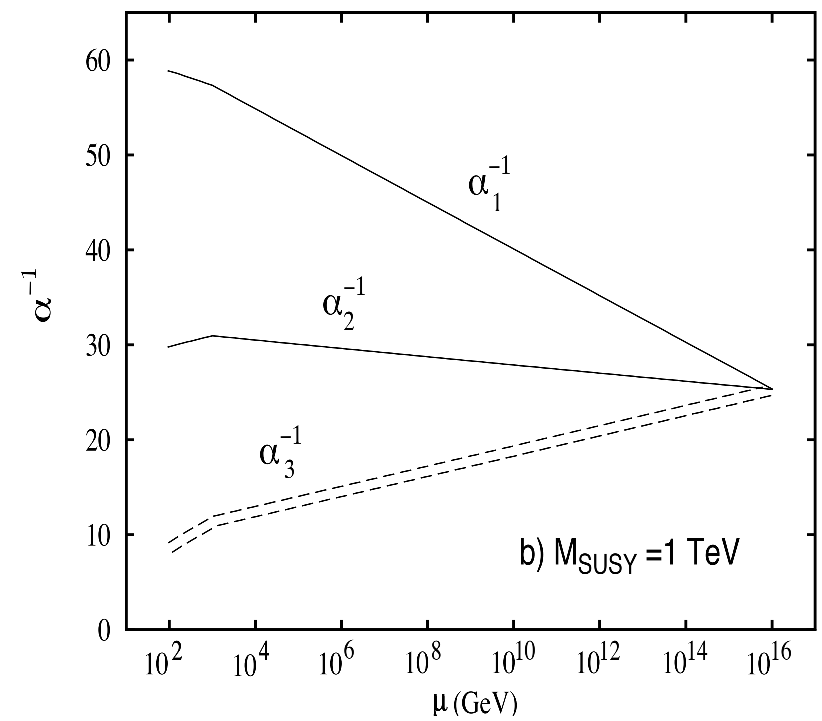
Leptogenesis and Grand Unification

SO(10) Grand Unified Theories (GUTs) = natural framework for heavy Majorana neutrinos:

$$SO(10) \supset SU(3)_C \times SU(2)_L \times U(1)_Y$$

(i) $\mathbf{16} \;=\; (Q, \bar{u}, \bar{d}, L, \bar{e}) \oplus \bar{N}$

(ii) B-L is a generator of SO(10) $\Rightarrow$ the mass scale of the N_R is associated with the breaking of the gauge group $\Rightarrow$ M_R >> Mweak natural



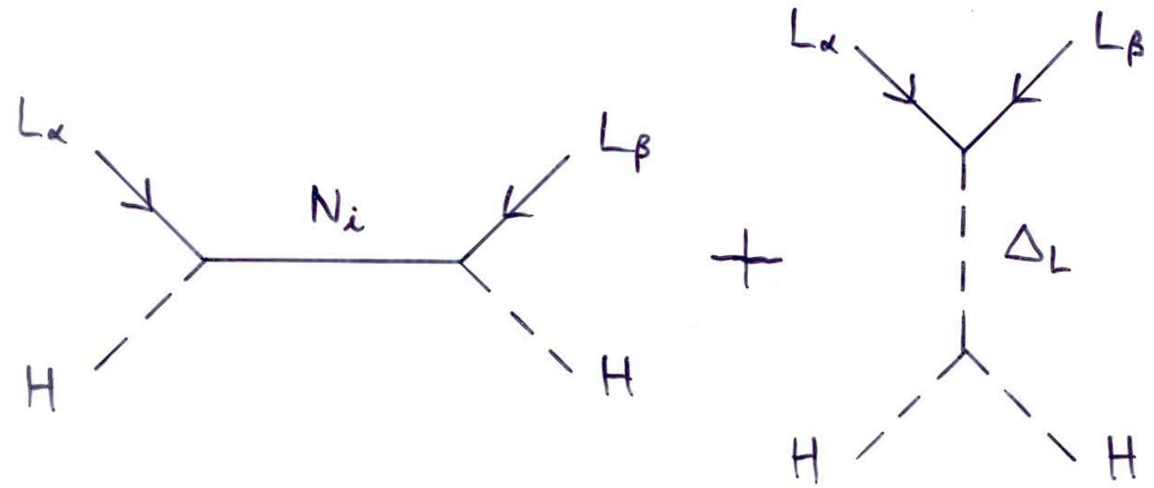
However, successful leptogenesis is not so easy to achieve in SO(10)

The simplest models (with Y = Yu) predict

$$M_1 \;:\; M_2 \;:\; M_3 \;\sim\; m_u^2 \;:\; m_c^2 \;:\; m_t^2 \;, \qquad \text{with } M_1 \sim 10^5\,\text{GeV}$$

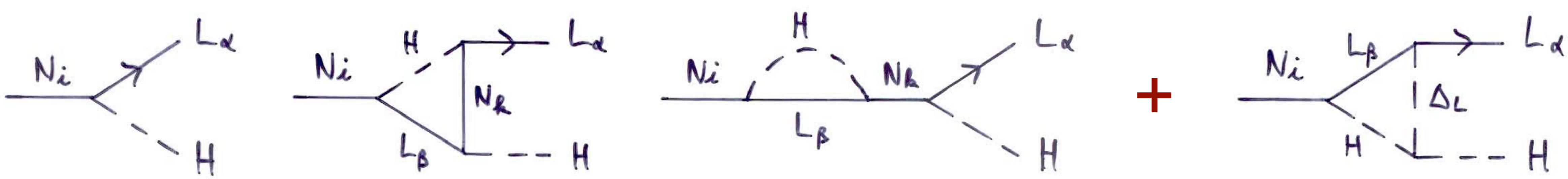
→ incompatible with successful leptogenesis

However, in SO(10) models with an underlying left-right symmetry, neutrino masses also receive contributions from an heavy SU(2)L triplet:



Δ_L = SU(2)$_L$ triplet with couplings $f_{\alpha\beta}$ to the leptons L_α

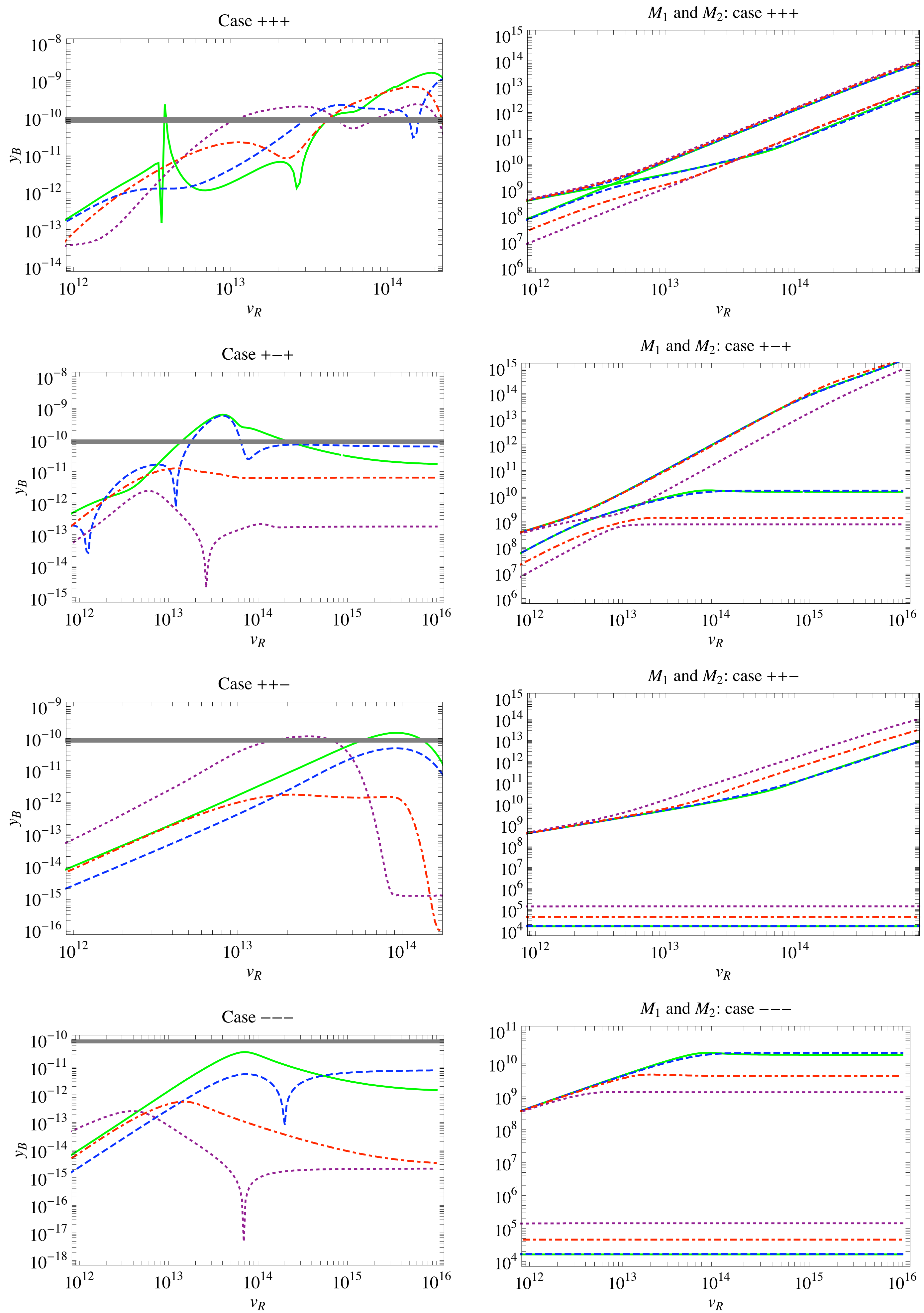
The SU(2)$_L$ triplet also contributes to leptogenesis. If $M_1 << M_\Delta$, it mainly affects leptogenesis by contributing to the CP asymmetry in N_1 decays:



[Hambye, Senjanovic]

The heavy neutrino masses and the triplet couplings to leptons are determined by the same parameters $f_{\alpha\beta}$. Possible to reconstruct the $f_{\alpha\beta}$ from low-energy data (neutrino masses and mixing angles) with minimal assumptions on the N_i couplings $\Rightarrow$ 8 solutions, some of which lead to successful leptogenesis

[Hosteins, SL, Savoy (2006)]

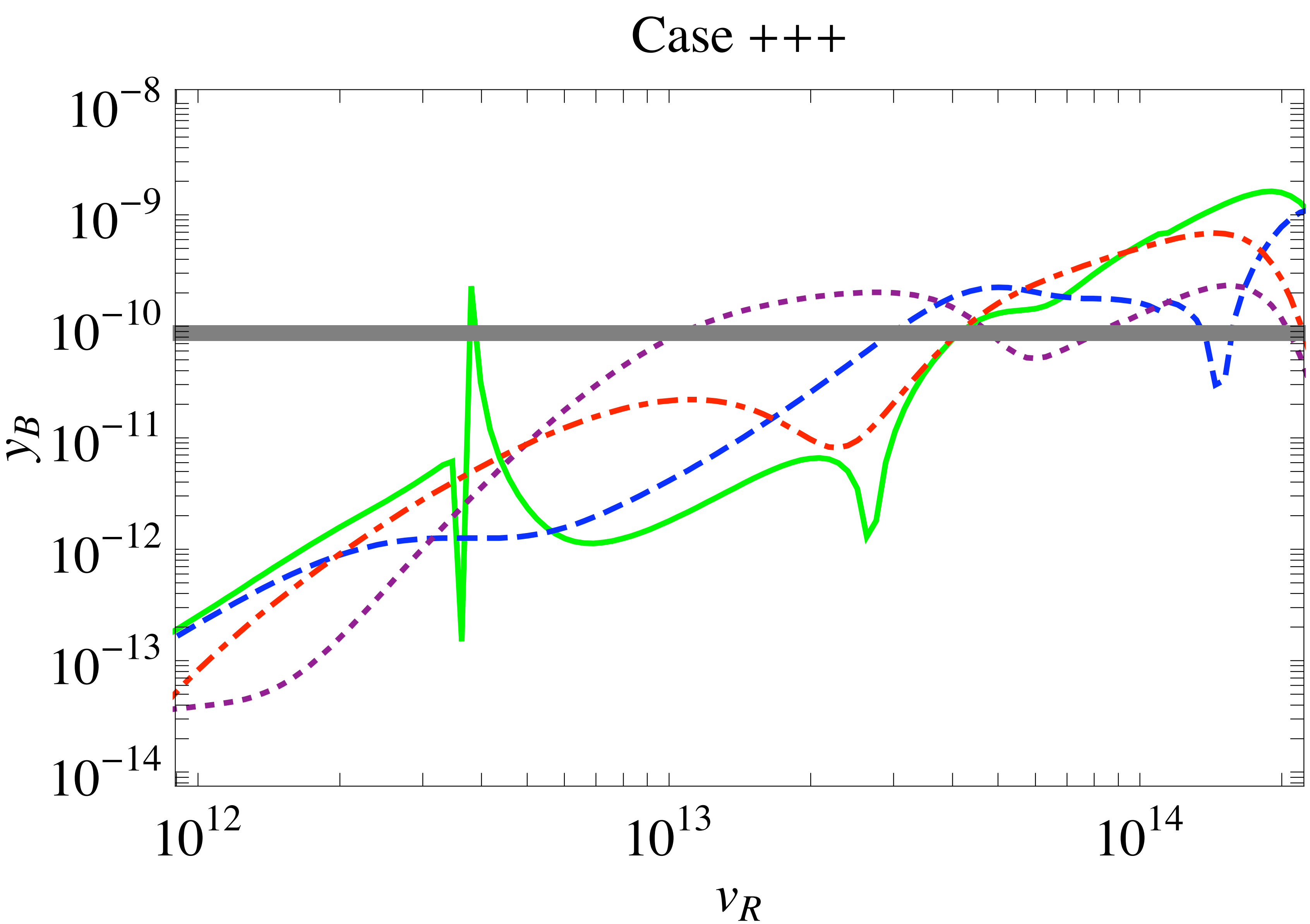


[Abada, Hosteins, Josse-Michaux, SL (2008)]

- flavour-dependent Boltzmann equations (independent evolution of the lepton asymmetry in the e, μ and τ flavours)
- contribution of N2
- Y = Yu [minimal SO(10) relation]
- corrections to Md = Me from non-renormalizable operators
- flavour-dependent "N2 leptogenesis" in the solutions with a light N1: N2 decays generate an asymmetry in a flavour that is only mildly washed out by N1 inverse decays

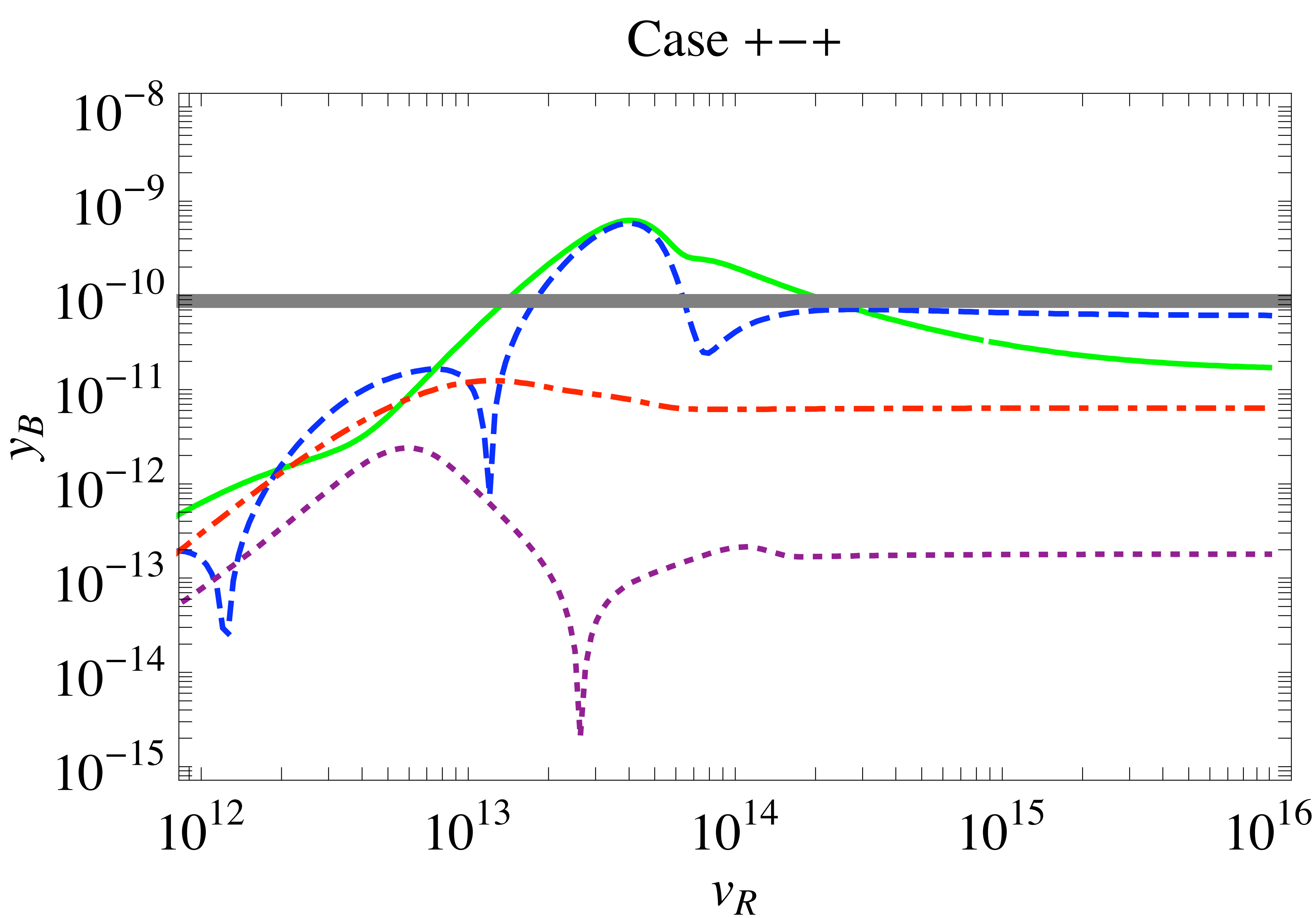
v_R = (B-L)-breaking scale

Inputs: normal hierarchy with $m_1 = 10^{-3}$ eV, $\theta_{13} = 0$, $\delta = 0$, different choices of Majorana and high-energy phases – $v^2 = 0.1\, v_L\, v_R$ – $T_{in} = 10^{11}$ GeV



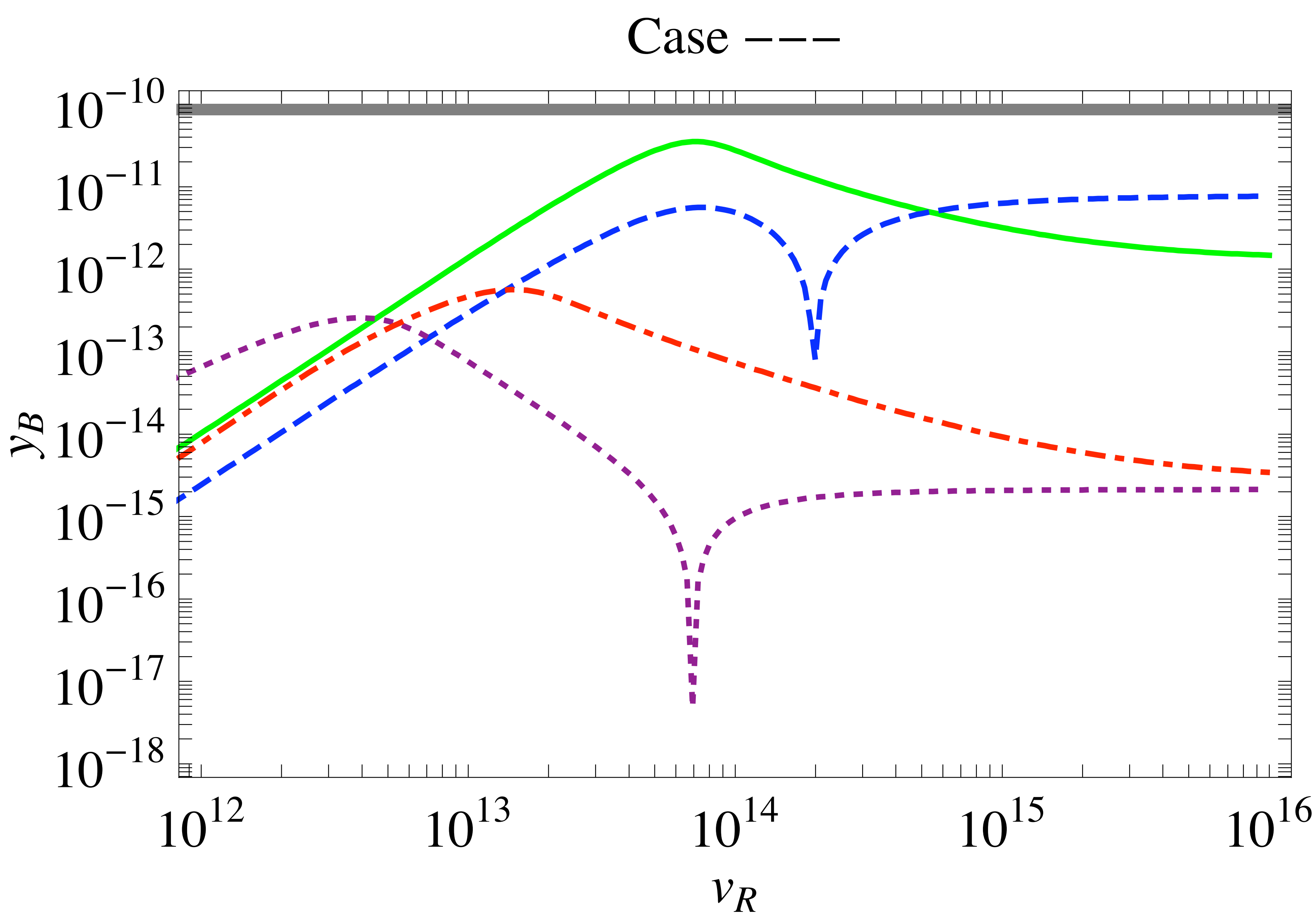
Successful leptogenesis possible for a (B-L)-breaking scale $v_R \gtrsim 10^{13}\,\mathrm{GeV}$

[Abada, Hosteins, Josse-Michaux, SL (2008)]



Successful leptogenesis possible for $v_R \sim (10^{13} - 10^{14})\,\mathrm{GeV}$

[Abada, Hosteins, Josse-Michaux, SL (2008)]



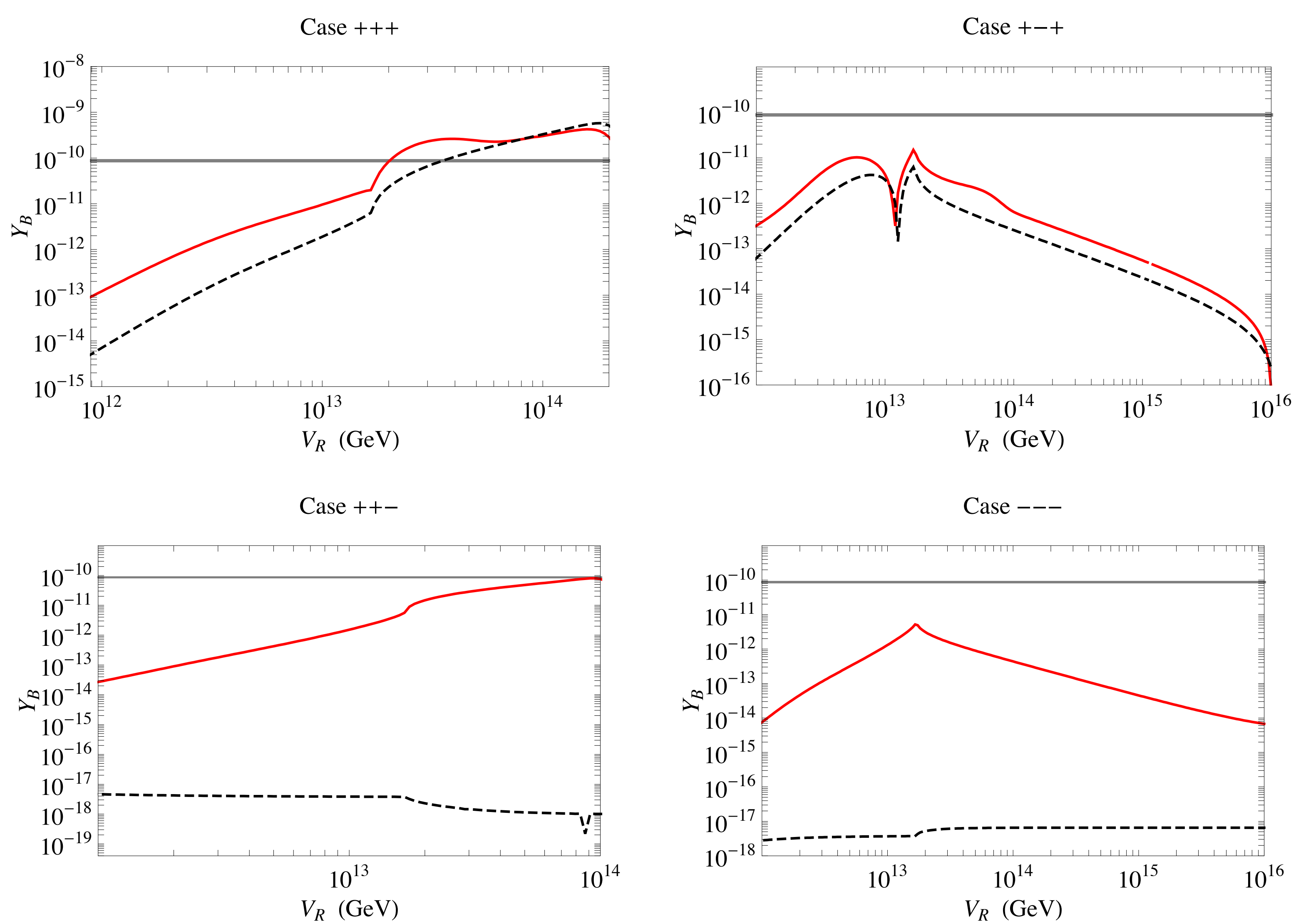
In spite of a huge enhancement by lepton flavour effects, the baryon asymmetry generated from N_2 decays fails to reproduce the observed value if $Y = Y_u$ (no successful set of parameters found) – also true for standard seesaw

[Abada, Hosteins, Josse-Michaux, SL (2008)]

Impact of lepton flavour effects

Quantative difference between the solution of the flavour-dependent Boltzmann equations (independent evolution of the lepton asymmetry in the e, μ and τ flavours) and the 1-flavour approximation

Particularly strong impact when N2 decays generate an asymmetry in a lepton flavour that is only mildly washed out by N1 inverse decays



flavour-dependent case

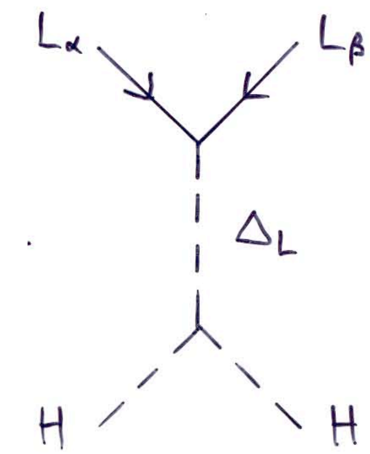
1-flavour approximation

[Abada, Hosteins, Josse-Michaux, SL (2008)]

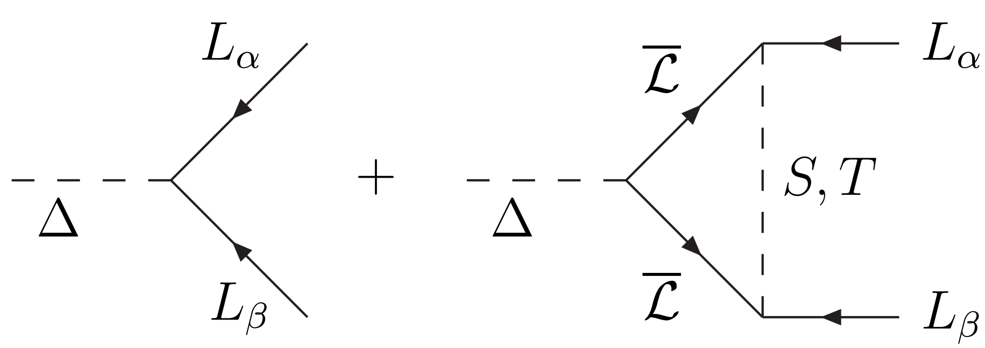
A predictive scheme for (triplet) leptogenesis

Another class of SO(10) models leads to pure triplet seesaw mechanism $\Rightarrow$ neutrinos masses proportional to triplet couplings to leptons:

$$(M_\nu)_{\alpha\beta} = \frac{\lambda_H f_{\alpha\beta}}{2M_\Delta} v^2$$



These models contain heavy (non-standard) leptons that induce a CP asymmetry in the heavy triplet decays



The SM and heavy lepton couplings are related by the SO(10) gauge symmetry, implying that the CP asymmetry in triplet decays can be expressed in terms of (measurable) neutrino parameters

→ important difference with other triplet leptogenesis scenarios

[Frigerio, Hosteins, SL, Romanino (2008)]

Dependence on the light neutrino parameters

$$\epsilon_\Delta \propto \frac{1}{(\sum_i m_i^2)^2} \Big\{ c_{13}^4 c_{12}^2 s_{12}^2 \sin(2\rho)\, m_1 m_2 \Delta m_{21}^2$$

$$+ c_{13}^2 s_{13}^2 c_{12}^2 \sin 2(\rho - \sigma)\, m_1 m_3 \Delta m_{31}^2 - c_{13}^2 s_{13}^2 s_{12}^2 \sin(2\sigma)\, m_2 m_3 \Delta m_{32}^2 \Big\}$$

$$U_{ei} = (c_{13} c_{12} e^{i\rho}, c_{13} s_{12}, s_{13} e^{i\sigma})$$

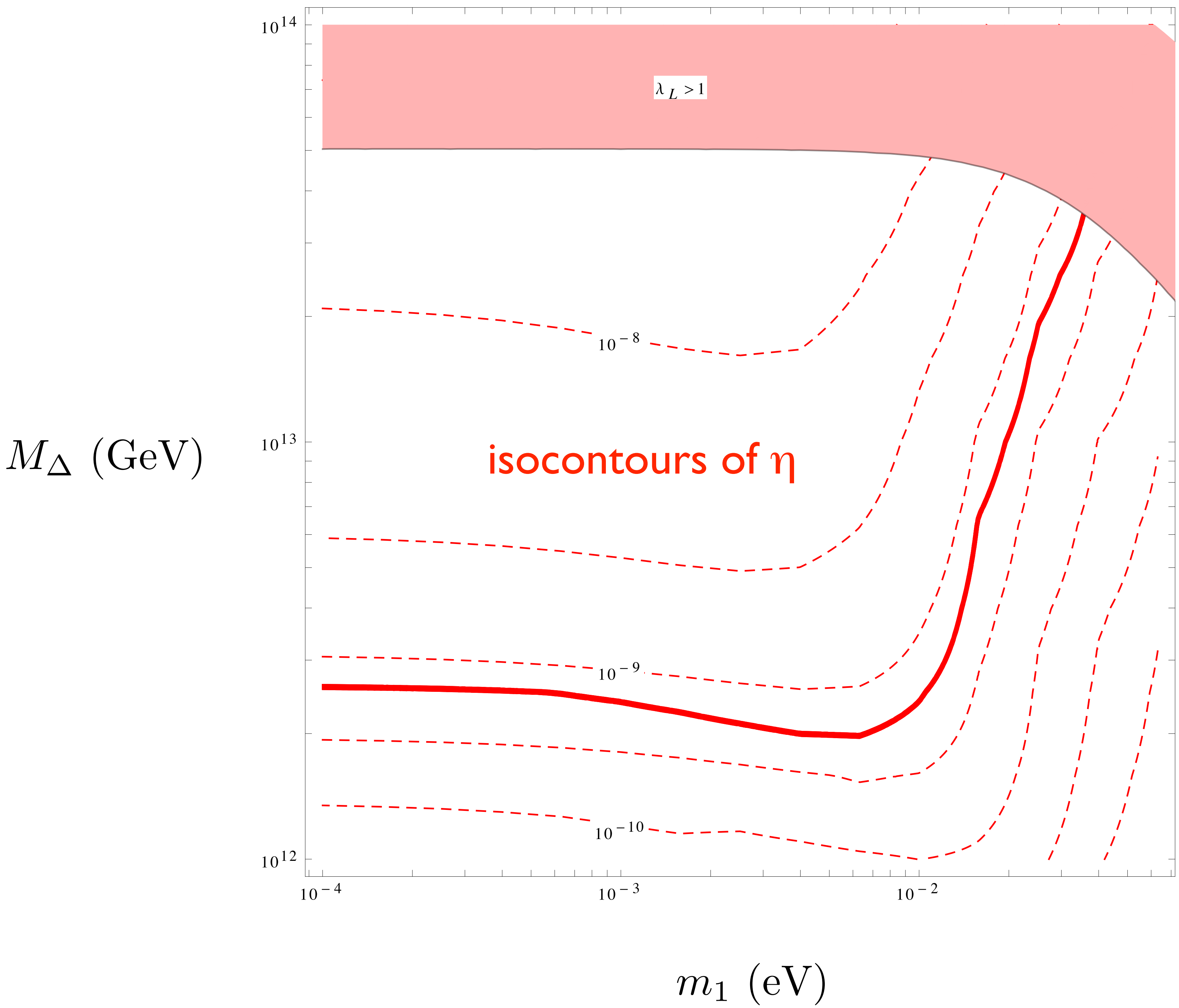
→ ϵ_Δ depends on measurable neutrino parameters

→ the CP violation needed for leptogenesis is provided by the CP-violating phases of the lepton mixing matrix (the Majorana phases to which neutrinoless double beta decay is sensitive)

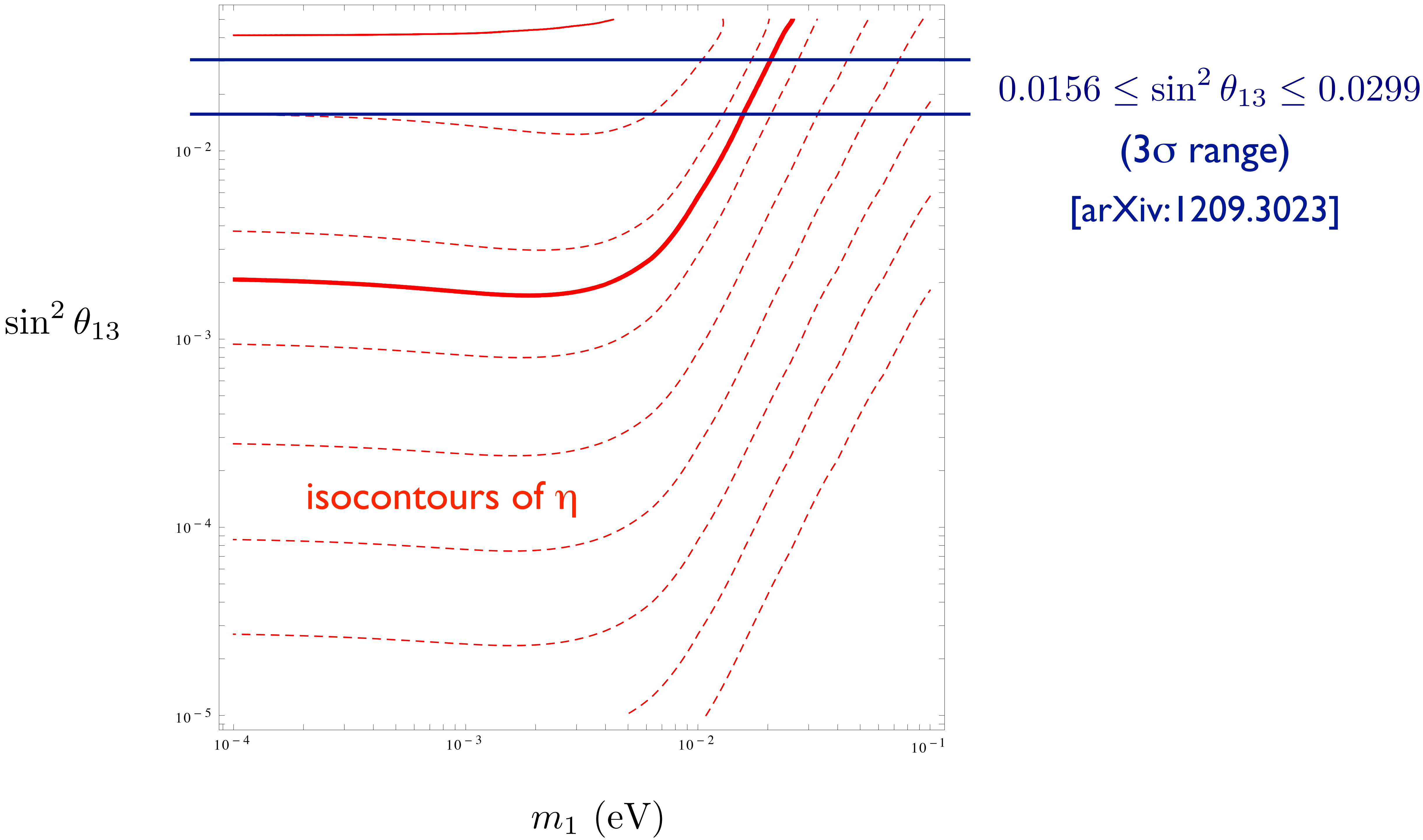
An approximate solution of the Boltzmann equations suggested that successful leptogenesis is possible if the "reactor" mixing angle θ_{13} is large enough (prior to its measurement by the Daya Bay experiment) [Frigerio, Hosteins, SL, Romanino (2008)]

→ confirmed by the numerical resolution of the flavour-dependent Boltzmann equations [SL, B. Schmauch, in progress]

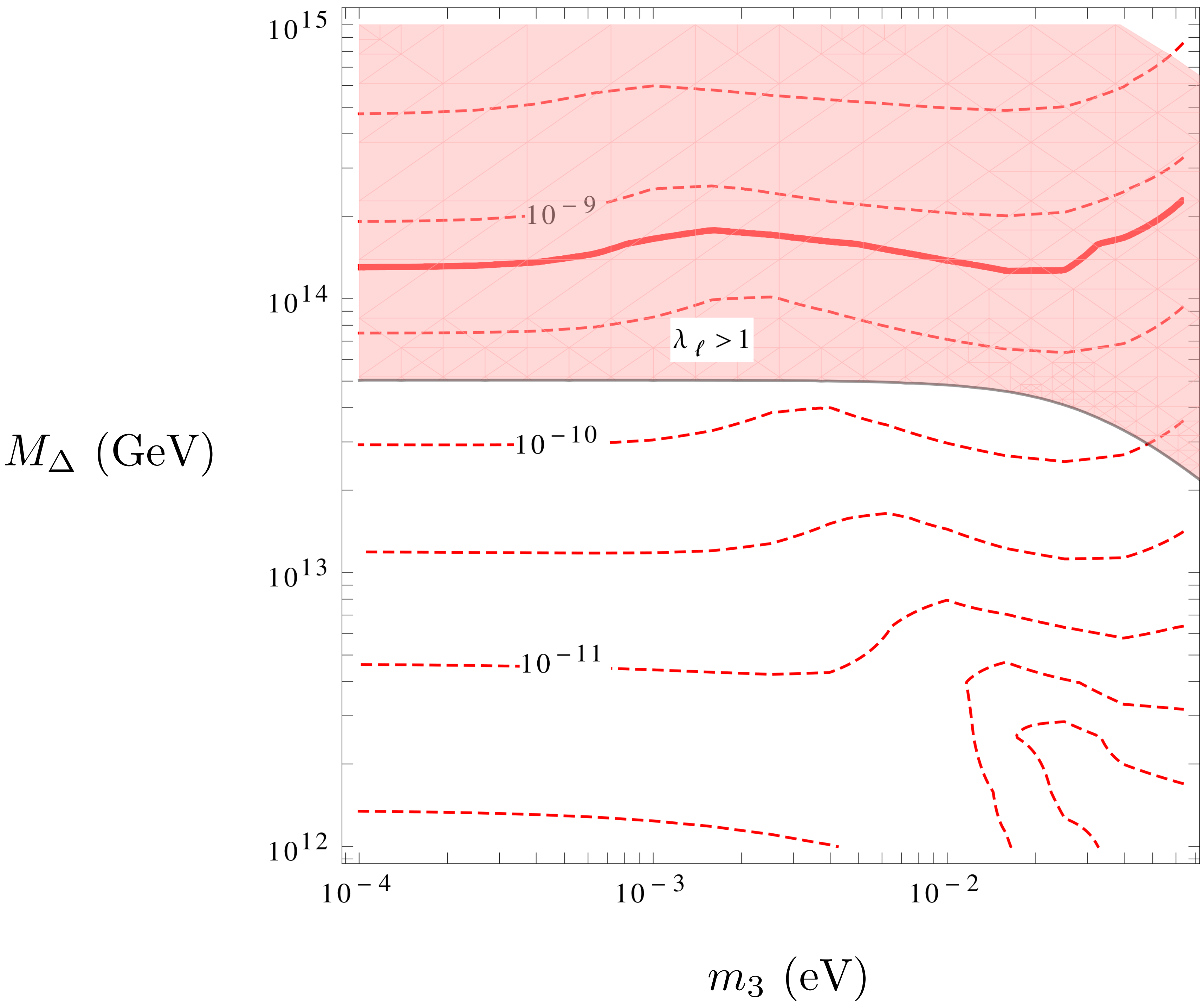
Parameter space allowed by successful leptogenesis



[SL, B. Schmauch (in progress)]



[SL, B. Schmauch (in progress)]



→ inverted hierarchy disfavoured

[SL, B. Schmauch (in progress)]

Conclusions

The observed baryon asymmetry of the Universe cannot be generated by standard electroweak baryogenesis, the only available mechanism within the Standard Model, and requires new physics

An attractive possibility is leptogenesis. Neutrino masses and the baryon asymmetry share a common origin, but this scenario cannot be directly tested (at least in its standard version)

Successful leptogenesis is compatible with Grand Unification, e.g.:

- SO(10) models with a left-right symmetric seesaw mechanism involving both heavy Majorana neutrinos and an electroweak triplet
- SO(10) models with pure triplet seesaw $\Rightarrow$ predictive leptogenesis

Although difficult to test, leptogenesis would gain support from:

- observation of neutrinoless double beta decay: $(A,Z) \rightarrow (A,Z+2)\ e^- e^-$ [proof of the Majorana nature of neutrinos - necessary condition]

- observation of CP violation in the lepton sector, e.g. in neutrino oscillations [neither sufficient nor necessary condition (*)]

- experimental exclusion of non-standard electroweak baryogenesis scenarios [e.g. MSSM with a light stop]

(*) in general, leptogenesis depends both on high-energy and low-energy (i.e. PMNS) phases

Back-up slides

At tree level and at T=0,

$$V_{tree}(\phi, T=0) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 \qquad m_H = \sqrt{2\lambda}v, \;\; v \equiv \langle\phi\rangle$$

1-loop effective potential at finite T (assuming λ small):

$$V_{1-loop}(\phi, T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda(T)}{4}\phi^4$$

$$D = \frac{2M_W^2 + M_Z^2 + 2m_t^2}{8v^2}, \quad E = \frac{2M_W^3 + M_Z^3}{4\pi v^3}, \quad T_0^2 \simeq \frac{m_H^2}{4D}, \quad \lambda(T) \simeq \lambda$$

The thermally generated cubic term induces a first order transition, with two degenerate minima at $T_c \simeq T_0/\sqrt{1 - E^2/(\lambda D)}$, Φ = 0 and

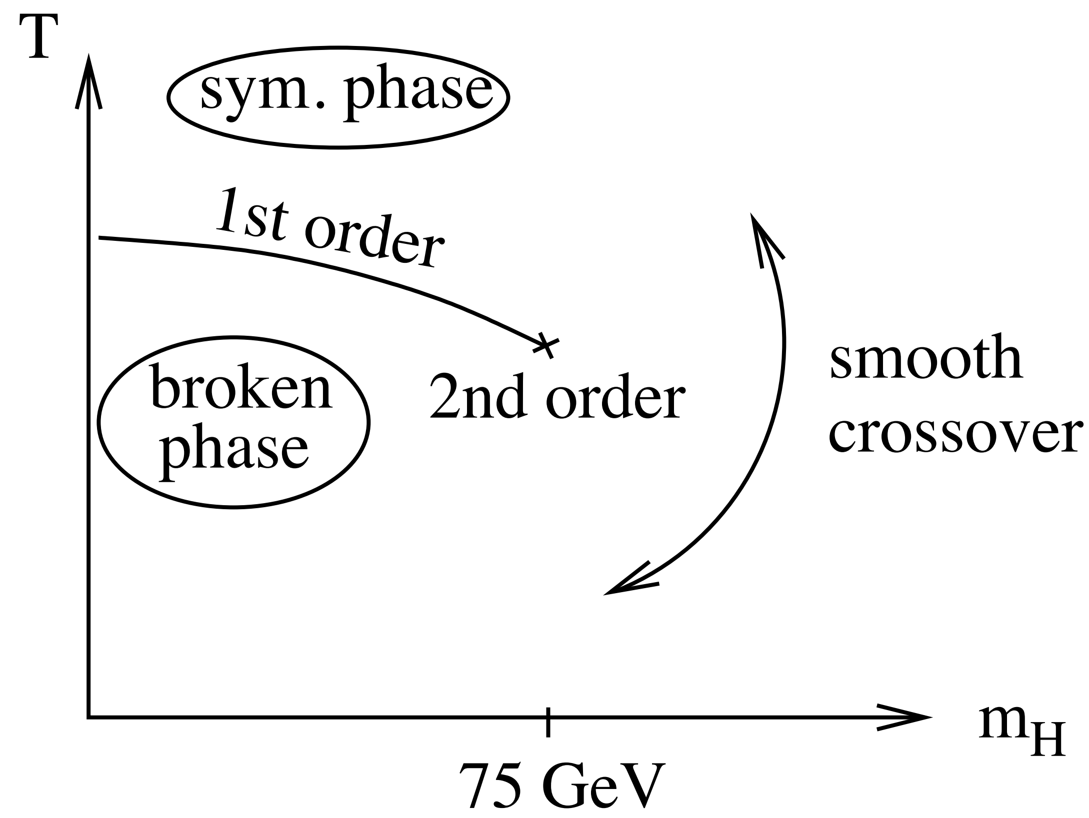
$$\phi(T_c) \;=\; \frac{2ET_c}{\lambda(T_c)} \;\simeq\; \frac{4Ev^2T_c}{m_H^2}$$

The out-of-equilibrium condition $\Phi(T_c)/T_c > 1$ then translates into:

$m_H \lesssim 40\,\mathrm{GeV}$ condition for a strong first order transition

⇒ excluded by LEP. Actually it has been shown that for $m_H \gtrsim 75\,\mathrm{GeV}$ there is no phase transition but a smooth crossover [Arnold]

Kajantie et al.
(hep-ph/9605228)



It is also generally admitted that CP-violating effects are too small in the SM for successful electroweak baryogenesis [Gavela, Hernandez, Orloff, Pène]

$\Rightarrow$ standard electroweak baryogenesis fails: the observed baryon asymmetry requires new physics beyond the Standard Model

Flavour effects in leptogenesis

Barbieri, Creminelli, Strumia, Tetradis
Endoh et al. - Nardi et al. - Abada et al.
Blanchet, Di Bari, Raffelt - Pascoli, Petcov, Riotto - ...

"one-flavour approximation": leptogenesis described in terms of a single direction in flavour space, the lepton $\mathcal{L}_1 \propto \sum_\alpha Y_{1\alpha} L_\alpha$ to which N_1 couples
$\Rightarrow$ valid as long as the charged lepton Yukawas λ_α are out of equilibrium

At $T \lesssim 10^{12}\,\mathrm{GeV}$, λ_τ is in equilibrium and destroys the coherence of $\mathcal{L}_1$
$\Rightarrow$ 2 relevant flavours: L_τ and a combination of L_e and L_μ

At $T \lesssim 10^{9}\,\mathrm{GeV}$, λ_τ and λ_μ are in equilibrium $\Rightarrow$ must distinguish between L_e , L_μ and L_τ

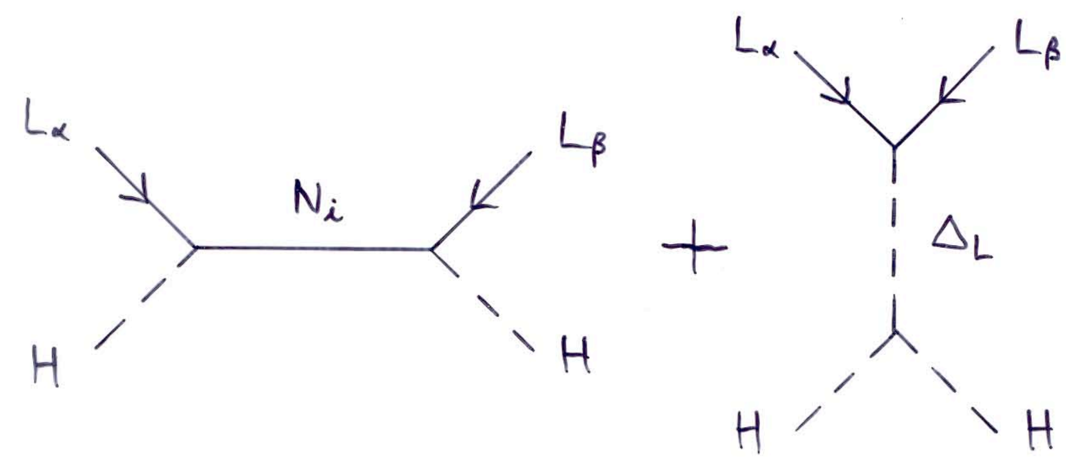
Relevant parameters for the discussion of flavour effects:

$$\epsilon^\alpha_{N_1} \equiv \frac{\Gamma(N_1 \to L_\alpha H) - \Gamma(N_1 \to \bar{L}_\alpha H^\star)}{\Gamma(N_1 \to L_\alpha H) + \Gamma(N_1 \to \bar{L}_\alpha H^\star)} \qquad \tilde{m}^\alpha_1 \equiv \frac{|Y_{1\alpha}|^2 v^2}{M_1}$$

qualitatively $Y_B \approx \sum_\alpha \epsilon^\alpha_{N_1} \eta(\tilde{m}^\alpha_1) \Rightarrow$ can deviate from the one-flavour approximation if e.g. $\epsilon^\tau_{N_1} \gg \epsilon^e_{N_1}, \epsilon^\mu_{N_1}$ and $\tilde{m}^\tau_1 \ll \tilde{m}^e_1, \tilde{m}^\mu_1$

SO(10) models with a left-right symmetric seesaw

Type I+II seesaw mechanism:



Δ_L = SU(2)L triplet with couplings f_{Lij} to lepton doublets

$$M_\nu \;=\; \frac{\lambda v^2}{M_\Delta}\, f_L - \frac{v^2}{v_R}\, Y^T f_R^{-1} Y$$

v_R = scale of B-L breaking (NR mass matrix: $M_R \;=\; f_R v_R$)

In a broad class of theories with underlying left-right symmetry (such as SO(10) with a $\overline{126}_H$), one has $Y = Y^T$ and $f_L = f_R \equiv f$:

$$M_\nu \;=\; v_L\, f - \frac{v^2}{v_R}\, Y f^{-1} Y$$

→ left-right symmetric seesaw mechanism

In explicit SO(10) models, Y is related to charged fermion Yukawa couplings ⇒ predictive framework

SO(10) models with type II seesaw mechanism

[Frigerio, Hosteins, SL, Romanino]

Much more difficult: NR's belong to the matter representation (16), hence are always around and couple to lepton doublets

<u>Way out</u>: "non-standard" embedding of the SM fermions into SO(10) representations

$$\begin{aligned} 16_i &= 10_i \oplus \;.\; \oplus 1_i \\ 10_i &= \;.\; \oplus \bar{5}_i^{10} \end{aligned}$$

$(5_i^{10}, \bar{5}_i^{16})$ form a vector-like pair of matter fields

$5_i^{10} \equiv (L_i^c, D_i)$ heavy anti-lepton doublets and quark singlets

SM matter fields: $10_i^{16} = (Q_i, u_i^c, e_i^c), \quad \bar{5}_i^{10} = (L_i, d_i^c), \quad 1_i^{16} = \nu_i^c$

<u>Neutrino masses</u>: no coupling of the NR's to the SM leptons at tree level
$\Rightarrow$ type II seesaw mechanism (in the presence of a 54 Higgs representation)

$$W_{II} = \frac{1}{2} f_{ij} 10_i 10_j 54 + \frac{1}{2} \sigma 10\, 10\, 54 + \frac{1}{2} M_{54} 54^2 \quad \Longrightarrow \quad M_\nu = \frac{\sigma (v_u^{10})^2}{2 M_\Delta} f$$

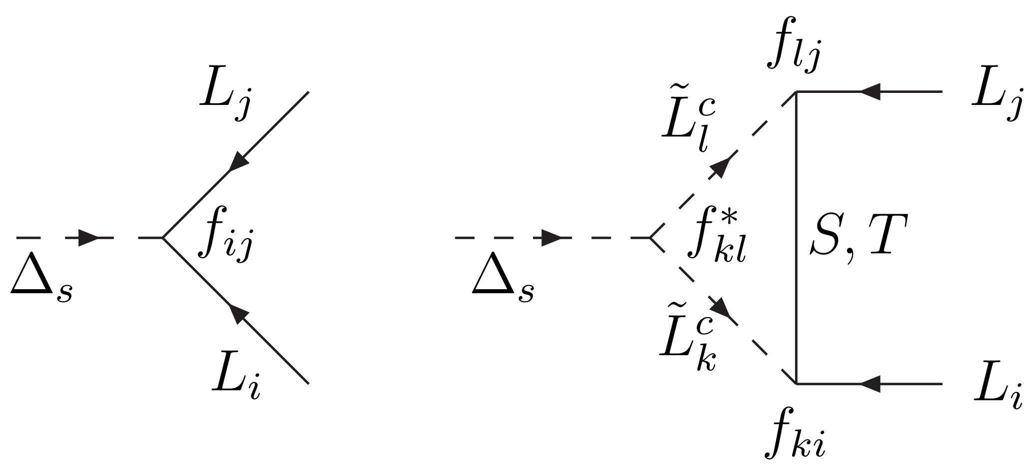
Leptogenesis

Requires a CP asymmetry in triplet decays. In standard triplet leptogenesis, the f_{ij} 's are not enough: need a second set of (flavour) couplings, otherwise

$$\epsilon_\Delta \propto \mathrm{Im}[\mathrm{Tr}(ff^*ff^*)] = 0$$

⇒ introduce e.g. a second triplet with couplings f'_{ij} to leptons
⇒ no direct connection between leptogenesis and neutrino masses

In our scenario, the states in the loop are heavy and the trace is incomplete



$$S, T \in 54$$

Assuming $M_1 \ll M_\Delta < M_1 + M_2$ and $M_S = M_T = M_{24} \gg M_\Delta$, one obtains:

$$\epsilon_\Delta \simeq \frac{1}{10\pi} \frac{M_\Delta}{M_{24}} \frac{\lambda_L^4}{\lambda_L^2 + \lambda_{L_1^c}^2 + \lambda_{H_u}^2 + \lambda_{H_d}^2} \frac{\mathrm{Im}[M_{11}(M^* M M^*)_{11}]}{(\sum_i m_i^2)^2}$$