Baryogenèse et leptogenèse

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- introduction
- the matter-antimatter asymmetry of the Universe
- the necessity of a dynamical generation mechanism
- the failure of baryogenesis in the Standard Model
- a link with neutrino masses: baryogenesis via leptogenesis
- alternative scenarios: scalar triplet and ARS leptogenesis
- conclusions

Journée P2I – Saclay, 23 janvier 2020

Introduction

The origin of the matter-antimatter asymmetry of the Universe is one of the big mysteries of particle physics and cosmology

Electroweak baryogenesis fails in the Standard Model $\Rightarrow$ new physics needed to modify the dynamics of the electroweak phase transition (+ new sources of CP violation), or different mechanism

Leptogenesis is an interesting possibility because it connects the baryon asymmetry of the Universe (BAU) to neutrino physics

In particular, leptogenesis requires CP violation: is it related to the CP violation searched for in long-baseline neutrino oscillation experiments?

More generally: can one probe/support leptogenesis with neutrino/particle physics experiments?

The observational evidence

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:

(i) light element abundances

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

$\Rightarrow$ remarkable agreement between the two:

$$\eta = (5.8 - 6.6) \times 10^{-10} \qquad \text{(BBN)}$$

$$\eta = (6.13 \pm 0.08) \times 10^{-10} \qquad \text{(Planck 2018)}$$

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, there is convincing evidence that our Universe 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

(iii) departure from thermal equilibrium

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 SM interactions (CP violation due to quark mixing: phase of the Cabibbo-Kobayashi-Maskawa matrix, responsible for CP violation in kaon decays)

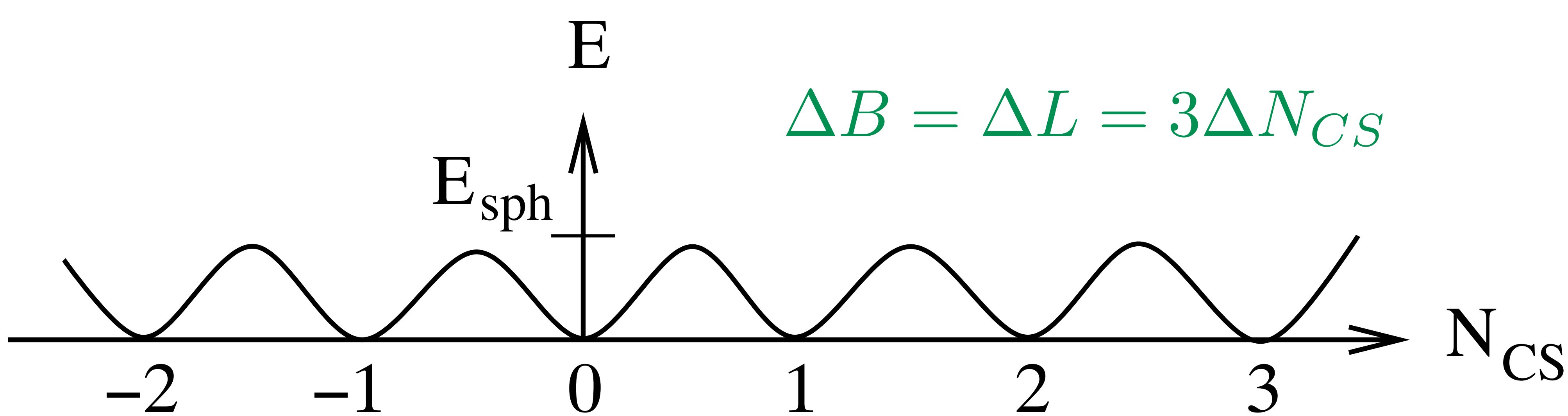
(iii) departure from thermal equilibrium can occur during the electroweak phase transition, during which particles acquire their masses

→ 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 $\Rightarrow$ non-perturbative processes (sphalerons) change the values of B and L [but preserve B-L]



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

In equilibrium above the EWPT [$T > T_{EW} \sim 100\,\mathrm{GeV}$, $\langle\phi\rangle = 0$]:

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

[Kuzmin, Rubakov, Shaposhnikov]

Exponentially suppressed below the EWPT [$0 < T < T_{EW}$, $\langle\phi\rangle \neq 0$]:

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

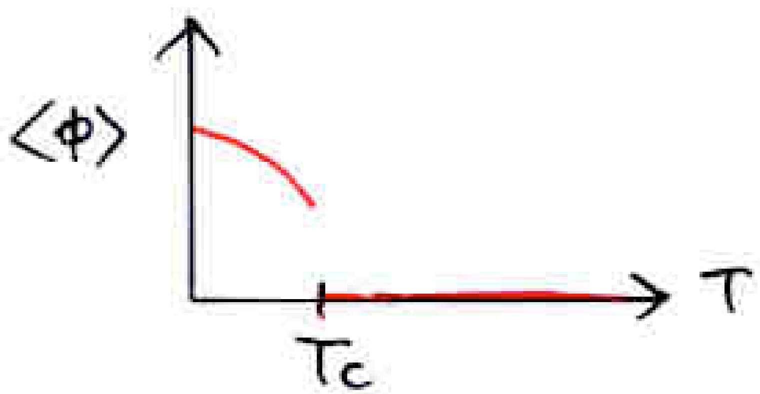
[Arnold, McLerran – Khlebnikov, Shaposhnikov]

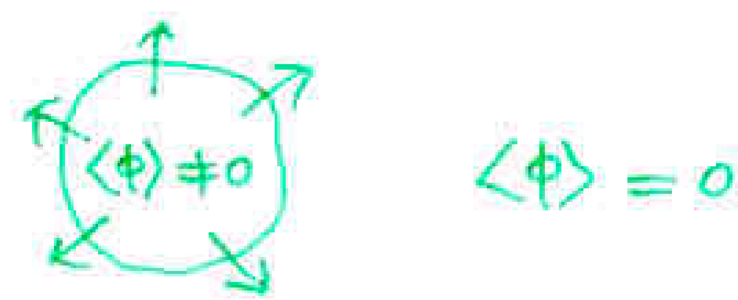
Baryogenesis in the Standard Model: rise and fall of electroweak baryogenesis

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 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

⇒ <u>excluded by LEP</u>

also not enough CP violation [small Jarlskog invariant] [Gavela, Hernandez, Orloff, Pene]

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

The observed baryon asymmetry requires new physics beyond the SM

⇒ <u>2 approaches:</u>

1) modify the dynamics of the electroweak phase transition [+ new source of CP violation needed] by adding new scalar fields coupling to the Higgs (2 Higgs doublet model, additional Higgs singlet…)

2) generate a B-L asymmetry at $T > T_{EW}$ (sphaleron processes violate baryon [B] and lepton [L] numbers, but preserve the combination B-L)

Leptogenesis (the generation of a lepton asymmetry in out-of-equilibrium decays of heavy states, which is partially converted into a B asymmetry by sphaleron processes) belongs to the second class

Intestingly, the existence of such heavy states is also suggested by neutrino oscillations, which require neutrinos to be massive

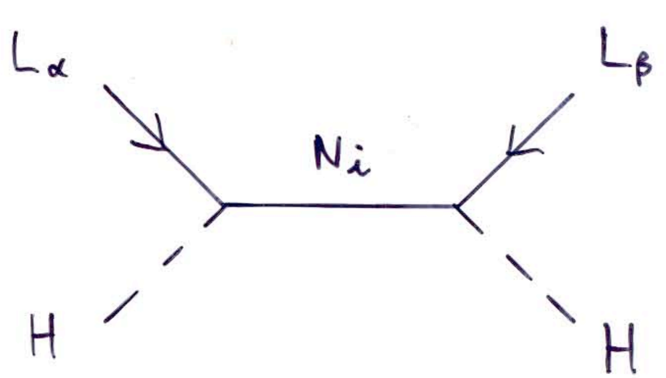
A link with neutrino masses: Baryogenesis via leptogenesis

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 there is flavour mixing in the lepton sector (PMNS matrix), as in the quark sector

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

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

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

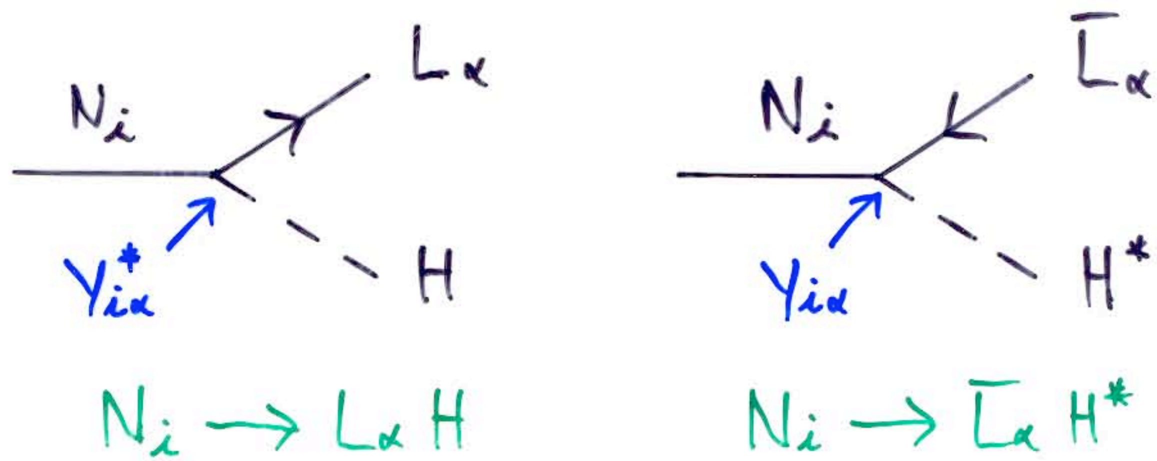


$$\Longrightarrow \qquad m_\nu \sim \frac{y^2 v^2}{M_R}$$

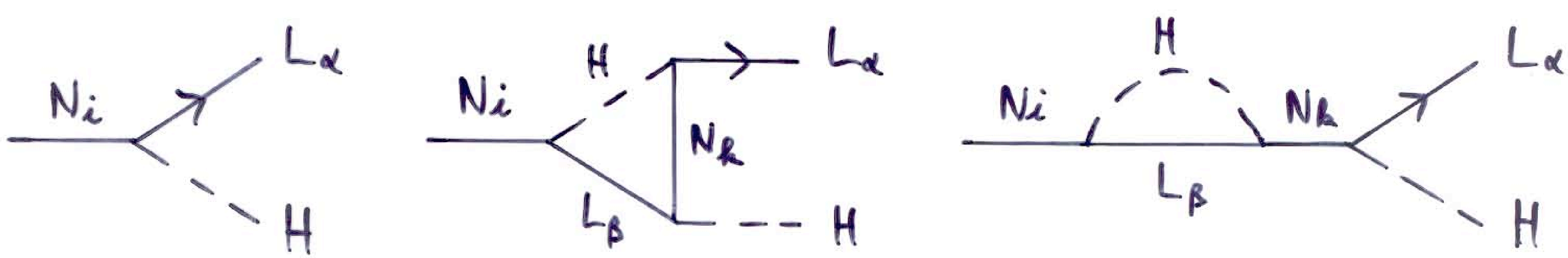
Minkowski - Gell-Mann, Ramond, Slansky
Yanagida - Mohapatra, Senjanovic

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 neutrinos) if their couplings to SM leptons violate CP

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



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



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

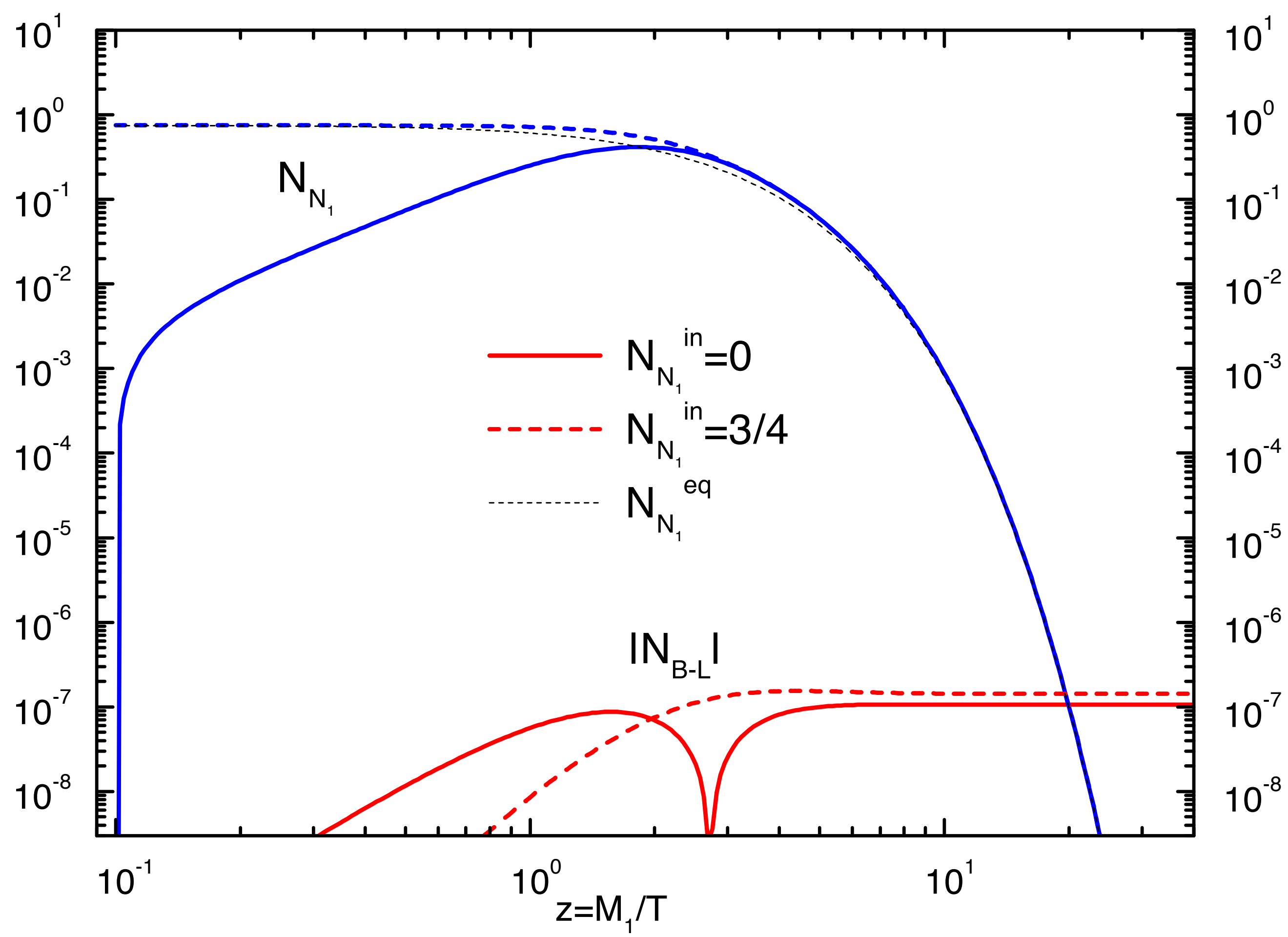
Covi, Roulet, Vissani '96
Buchmüller, Plümacher '98

The generated asymmetry is partly washed out by L-violating processes. Its evolution is described by the Boltzmann equation

$$sHz\,\frac{dY_L}{dz} = \left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}} - 1\right)\gamma_D\,\epsilon_{N_1} - \frac{Y_L}{Y_\ell^{\rm eq}}\left(\gamma_D + \gamma_{\Delta L=1} + \gamma_{\Delta L=2}\right)$$

$$Y_X \equiv \frac{n_X}{s} \qquad Y_L \equiv Y_\ell - Y_{\bar\ell} \qquad z \equiv \frac{M_1}{T}$$

Typical evolution:



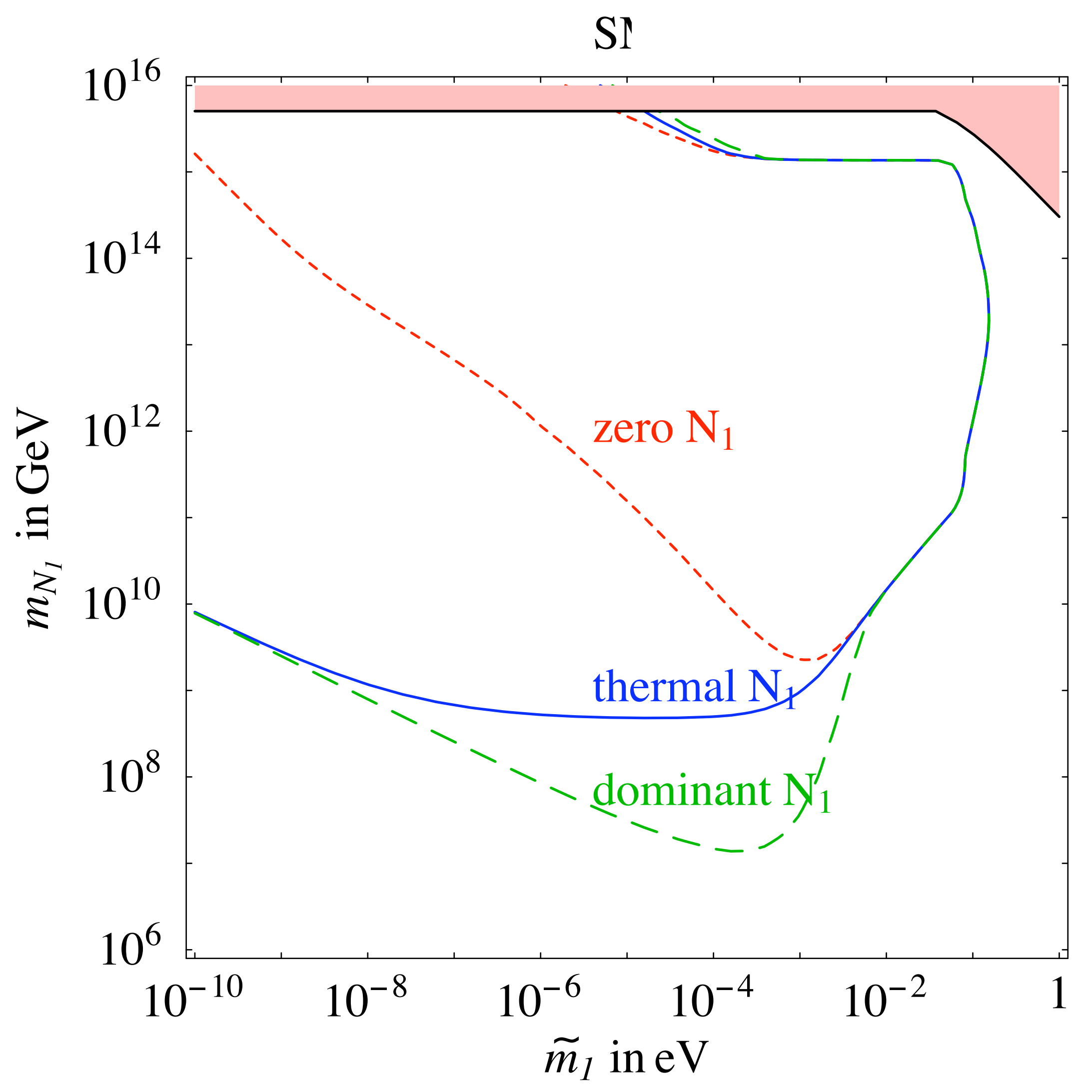
[Buchmüller, Di Bari, Plümacher '02]

Leptogenesis can explain the observed baryon asymmetry

region of successful leptogenesis in the $(\tilde{m}_1, M_1)$ plane

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

[Giudice, Notari, Raidal, Riotto, Strumia '03]



$\Rightarrow$ $M_1 \geq (0.5 - 2.5) \times 10^9\,\mathrm{GeV}$ depending on the initial conditions

[Davidson, Ibarra '02]

$M_1 \ll 10^9\,\mathrm{GeV}$ possible for $M_1 \approx M_2$ ("resonant leptogenesis")

[Covi, Roulet, Vissani - Pilaftsis]

A lot of theoretical progress on leptogenesis over the past 15 years:

- refinement of the calculation of the generated baryon asymmetry in the standard scenario with RH neutrinos (finite temperature corrections, spectator processes, lepton flavour effects, quantum Boltzmann equations)

- alternative scenarios to the standard one, including low-scale scenarios such as the ARS mechanism (CP-violating oscillations of sterile neutrinos around the EW scale) [Akhmedov, Rubakov, Smirnov '98]

- attempts to relate leptogenesis to measurable parameters, in particular to CP violation in neutrino oscillations (no direct connection in general)

Flavour effects in leptogenesis

Barbieri, Creminelli, Strumia, Tetradis '99
Endoh et al. '03 - Nardi et al. '06 - Abada et al. '06
Blanchet, Di Bari, Raffelt '06 - Pascoli, Petcov, Riotto '06

"One-flavour approximation" (1FA): leptogenesis described in terms of a single direction in flavour space, the lepton ℓ_{N_1} to which N_1 couples

$$\sum_\alpha Y_{1\alpha} \bar{N}_1 \ell_\alpha H \;\equiv\; y_{N_1} \bar{N}_1 \ell_{N_1} H \qquad\qquad \ell_{N_1} \;\equiv\; \sum_\alpha Y_{1\alpha} \ell_\alpha / y_{N_1}$$

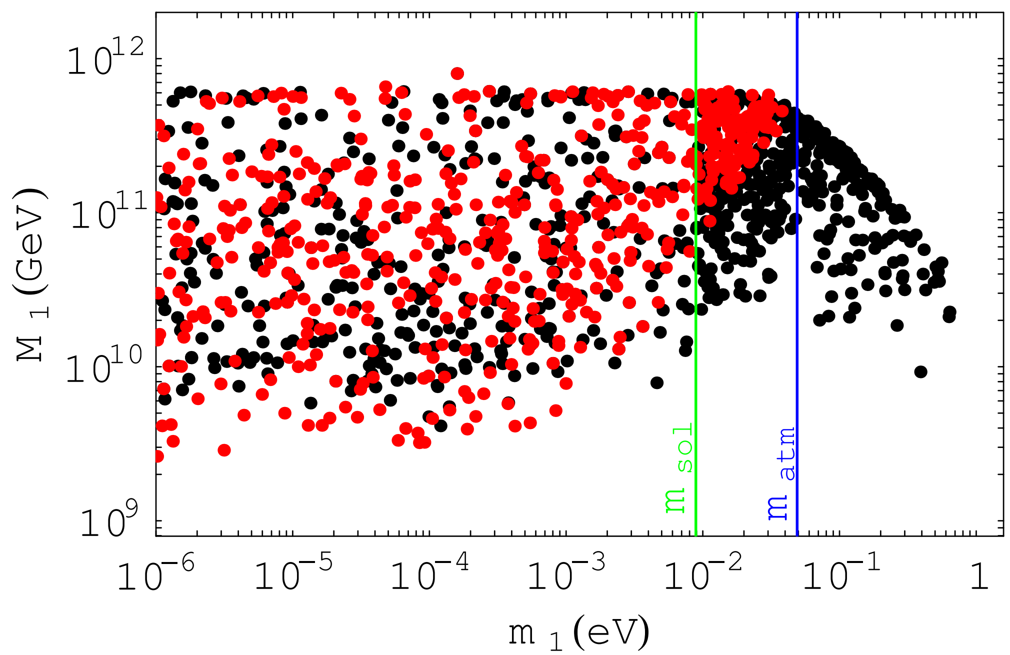
This is valid as long as the charged lepton Yukawas λ_α are out of equilibrium

At $T \lesssim 10^{12}\,\mathrm{GeV}$, λ_τ is in equilibrium and destroys the coherence of ℓ_{N_1}
$\Rightarrow$ 2 relevant flavours: ℓ_τ and a combination ℓ_a of ℓ_e and ℓ_μ

At $T \lesssim 10^9\,\mathrm{GeV}$, λ_τ and λ_μ are in equilibrium $\Rightarrow$ must distinguish ℓ_e, ℓ_μ and ℓ_τ

→ depending on the temperature regime, must solve Boltzmann equations for 1, 2 or 3 lepton flavours

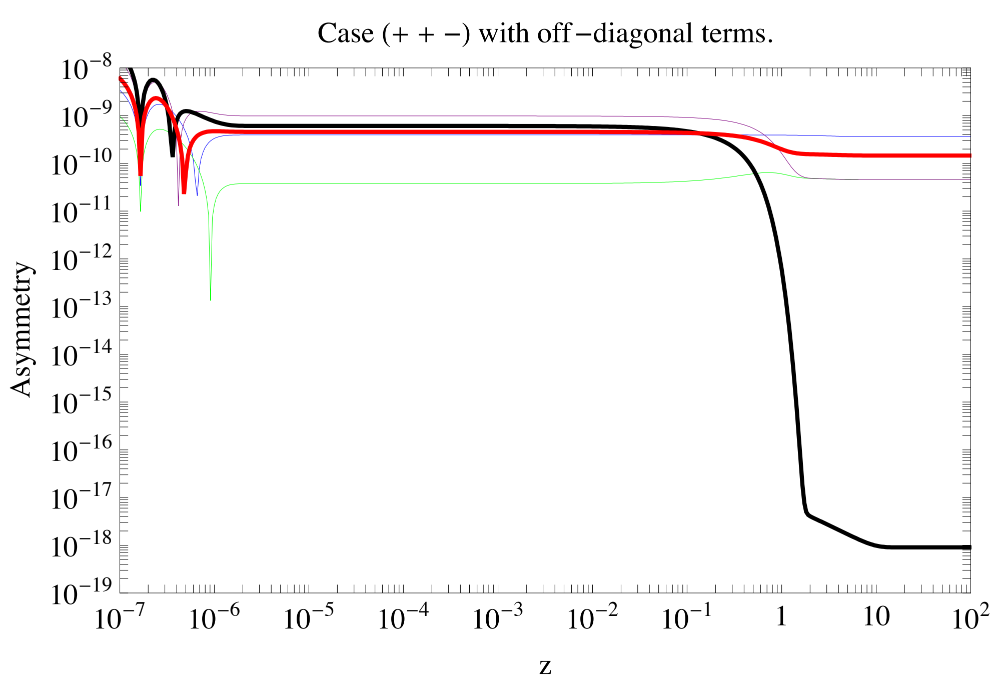
Flavour effects lead to quantitatively different results from the 1FA



red: 1FA
black: flavoured case

[Abada, Josse-Michaux '07]

Spectacular enhancement of the final asymmetry in some cases, such as N2 leptogenesis (N2 generate an asymmetry in a flavour that is only mildly washed out by N1) [Vives '05 - Abada, Hosteins, Josse-Michaux, SL '08 - Di Bari, Riotto '08]



[Abada, Hosteins, Josse-Michaux, SL '08]

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 UPMNS $\begin{cases} \delta & \to \text{oscillations} \\ \phi_2, \phi_3 & \to \text{neutrinoless double beta} \end{cases}$

→ are they related?

$$Y = \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix} R \begin{pmatrix} \sqrt{m_1} & 0 & 0 \\ 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{pmatrix} U^\dagger$$

[Casa, Ibarra]

3 heavy Majorana masses Mi

9 low-energy parameters $(m_i, \theta_{ij}, \delta, \phi_i)$

complex 3x3 matrix satisfying $RR^T = 1 \Rightarrow$ 3 complex parameters

$$YY^\dagger = \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix} R \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} R^\dagger \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix}$$

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

⇒ unrelated to CP violation at low-energy, except in specific 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

leptogenesis from the PMNS phase δ

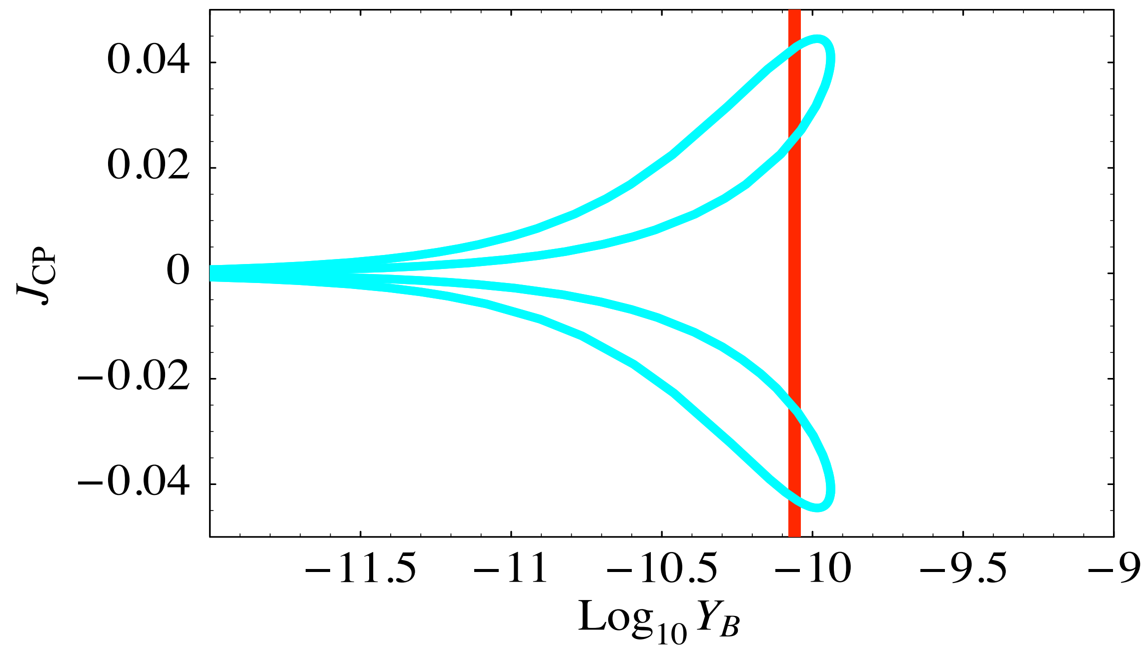


FIG. 1. The invariant $J_{\rm CP}$ versus the baryon asymmetry varying (in blue) $\delta = [0, 2\pi]$ in the case of hierarchical RH neutrinos and NH light neutrino mass spectrum for $s_{13} = 0.2$, $\alpha_{32} = 0$, $R_{12} = 0.86$, $R_{13} = 0.5$ and $M_1 = 5 \times 10^{11}$ GeV . The red region denotes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

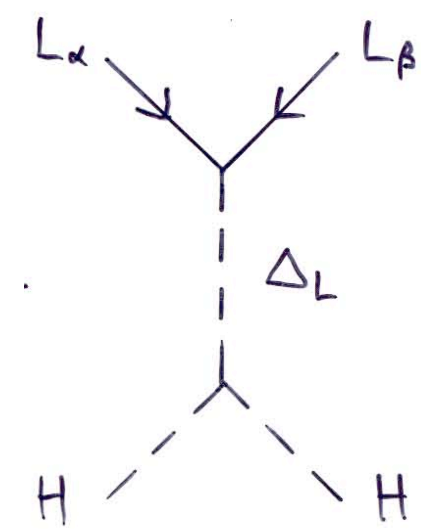
[Pascoli, Petcov, Riotto]

→ the discovery of CP violation in oscillations would not test directly leptogenesis, but would give some support to it

→ similarly, the observation of neutrinoless double beta decay would prove that lepton number is violated, another necessary condition for leptogenesis

An alternative scenario: scalar triplet leptogenesis

Alternative to heavy Majorana neutrinos: the SM neutrino masses may be generated by a heavy scalar (electroweak) triplet

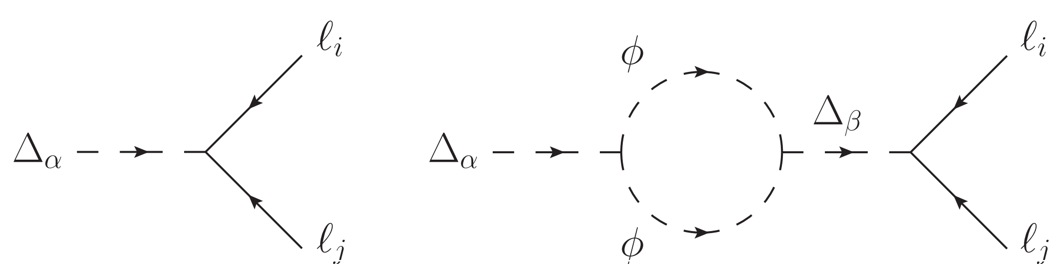


$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$ electroweak triplet

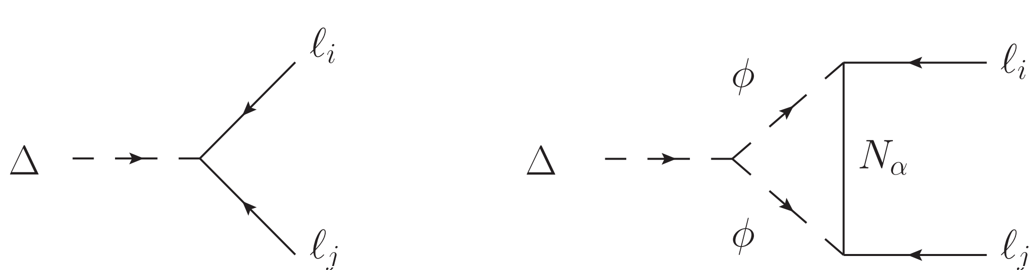
generates a neutrino mass $m_\nu = \dfrac{\mu\lambda_\ell}{2M_\Delta^2}\, v^2$

Also leads to leptogenesis if another heavy state couples to leptons

$\Rightarrow$ CP asymmetry in triplet decays [Ma, Sarkar '98 - Hambye, Senjanovic '03]



additional triplets



RH neutrinos

Inclusion of flavour effects in scalar triplet leptogenesis

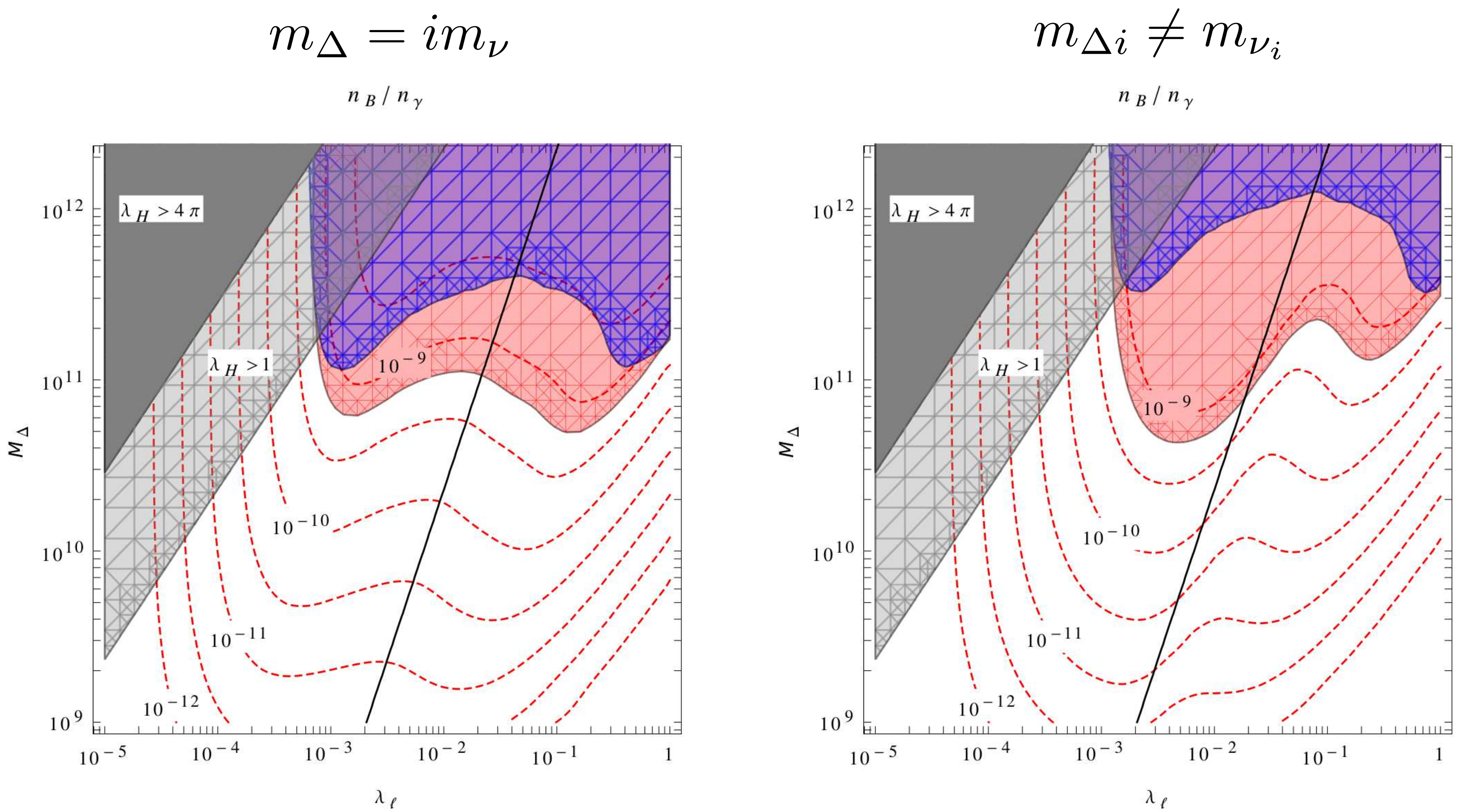


Figure 11: Isocurves of the baryon-to-photon ratio n_B/n_γ in the (λ_ℓ, M_Δ) plane obtained performing the full computation, assuming Ansatz 1 (left panel) or Ansatz 2 with $(x, y) = (0.05, 0.95)$ (right panel). The coloured regions indicate where the observed baryon asymmetry can be reproduced in the full computation (light red shading) or in the single flavour approximation with spectator processes neglected (dark blue shading). The solid black line corresponds to $B_\ell = B_H$. Also shown are the regions where λ_H is greater than 1 or 4π.

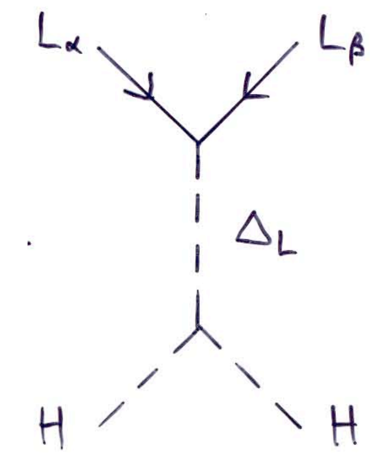
$M_\Delta > 4.4 \times 10^{10}$ GeV $\quad$ (1.2×10^{11} GeV without flavour effects)

[SL, Schmauch '15]

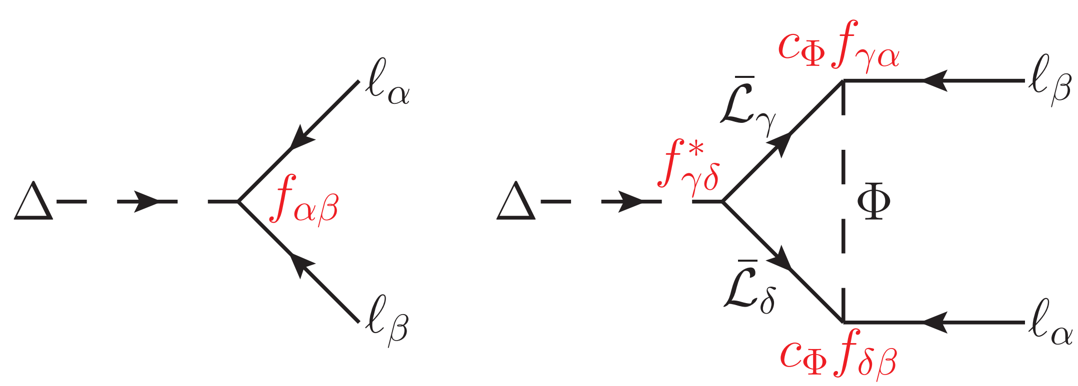
A predictive scheme for scalar triplet leptogenesis

Non-standard SO(10) model that leads to pure type II seesaw mechanism $\Rightarrow$ neutrinos masses proportional to triplet couplings to leptons:

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



This model also contains heavy (non-standard) leptons that induce a CP asymmetry in the heavy triplet decays



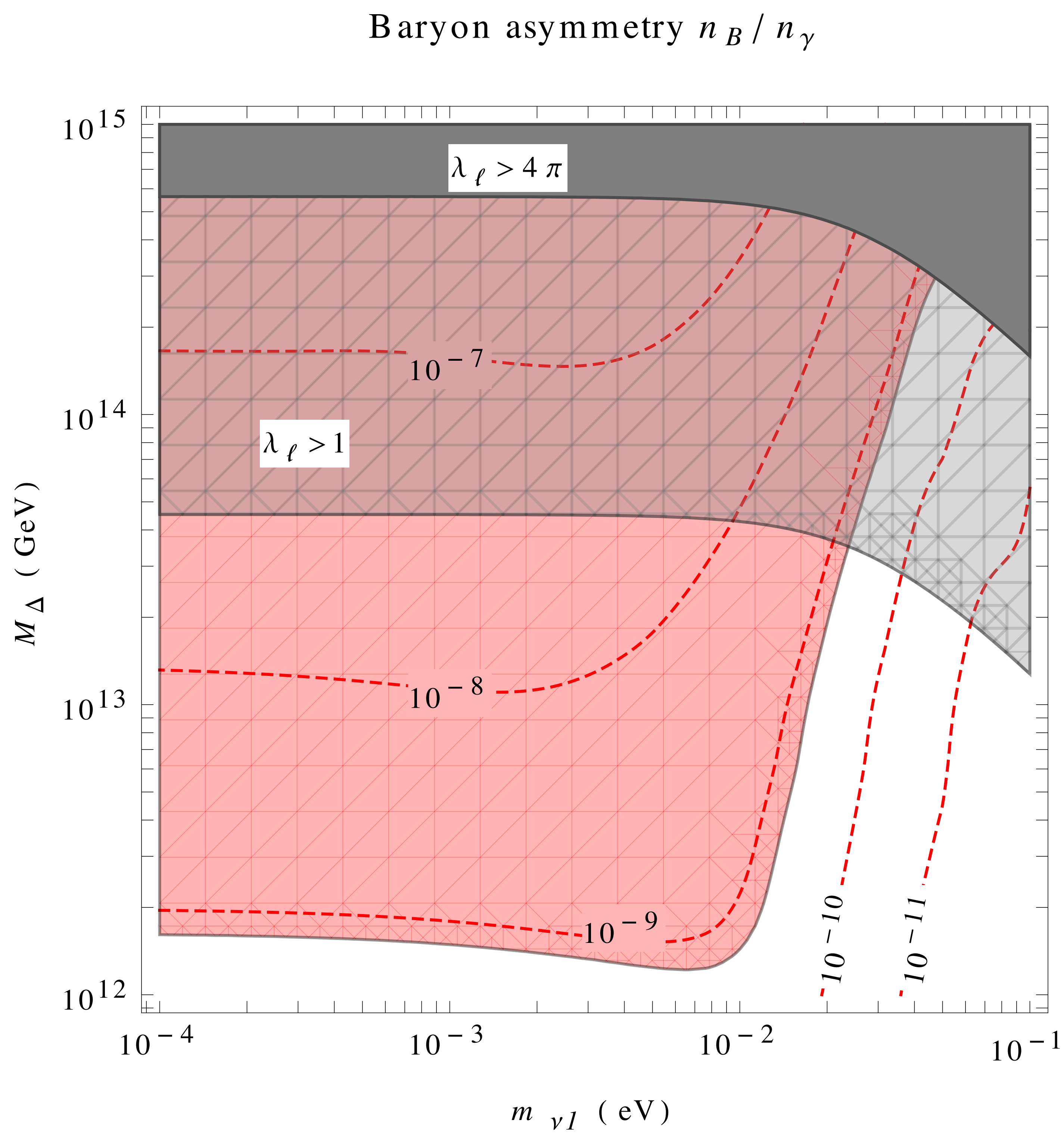
$$\Phi = S, T \in 54$$

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 '08]

Parameter space allowed by successful leptogenesis: normal hierarchy



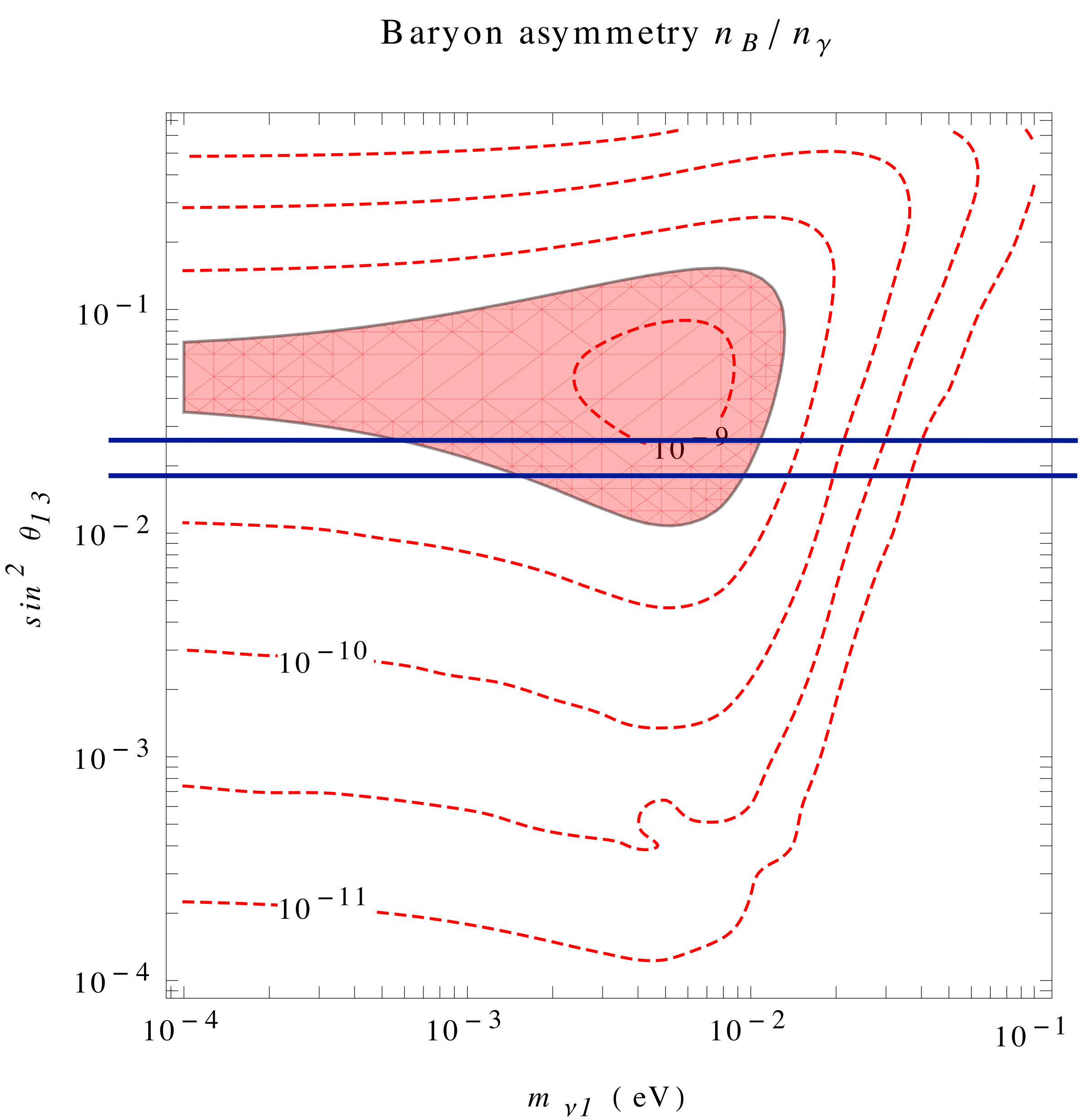
$\lambda_H = 0.2$

→ excludes a quasi-degenerate spectrum

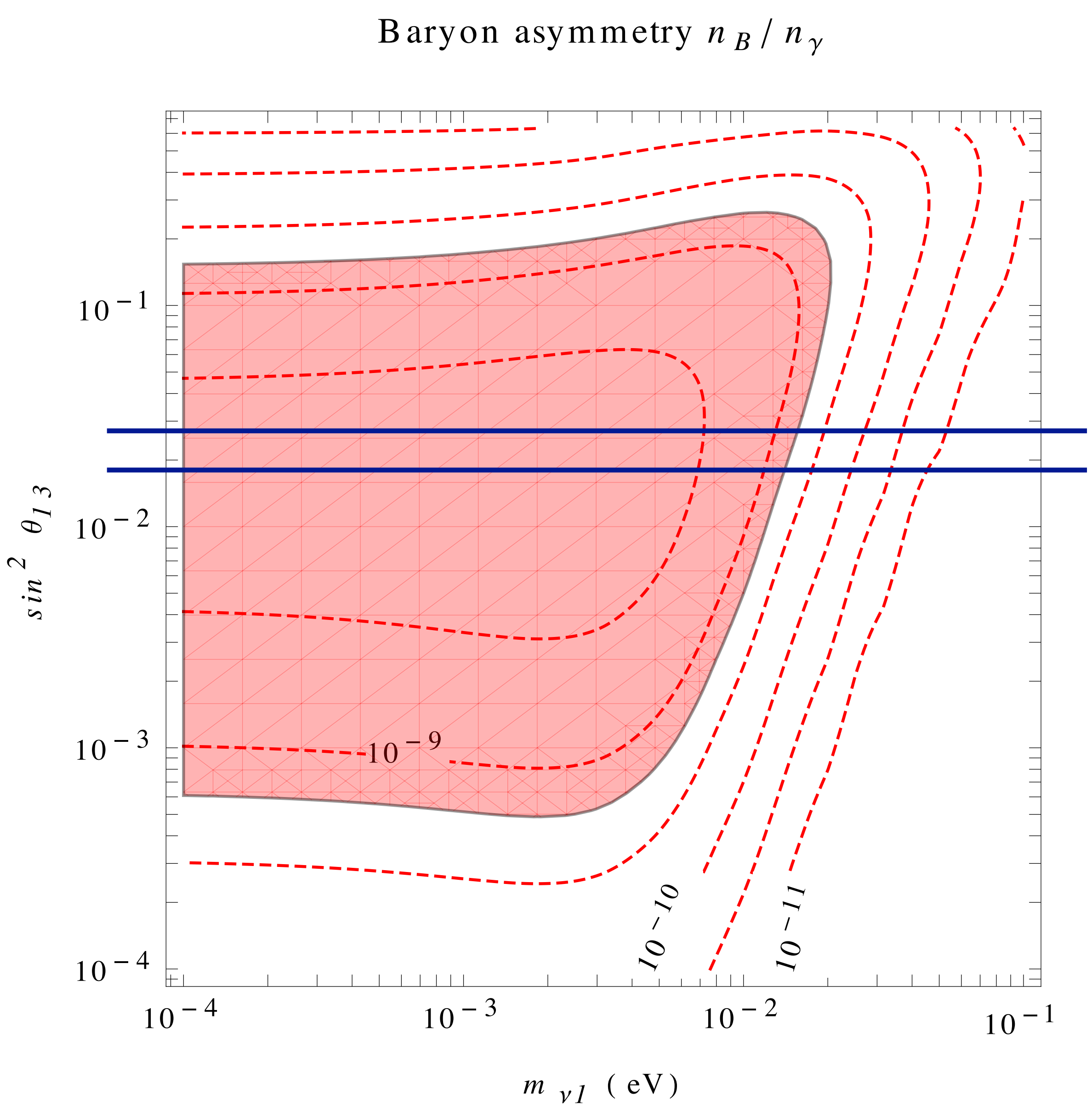
[SL, Schmauch, en préparation]

θ_{13} dependence

$M_\Delta = 1.5 \times 10^{12}\,\mathrm{GeV}$



$M_\Delta = 5 \times 10^{12}\,\mathrm{GeV}$

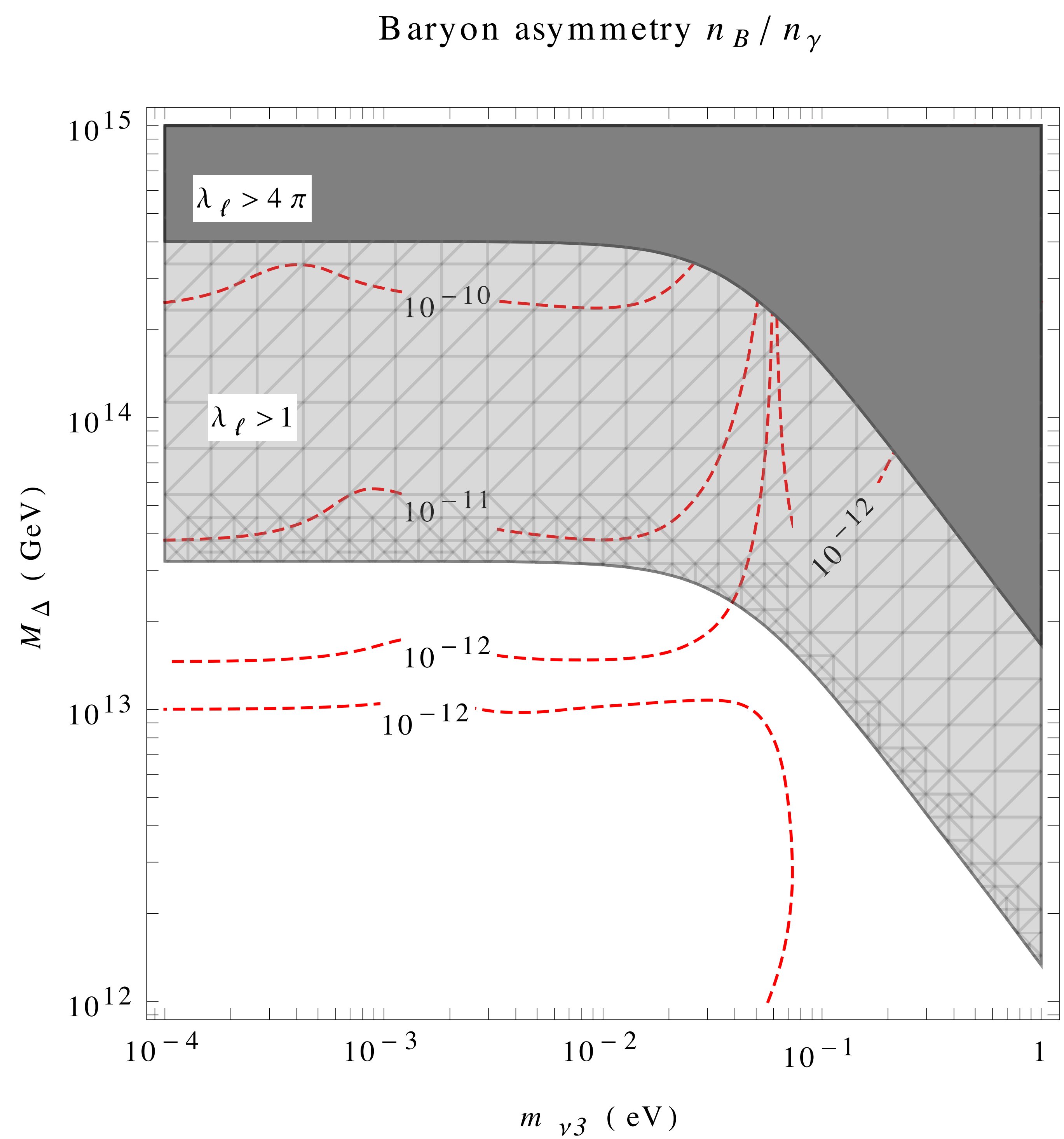


(3σ range)

$\lambda_H = 0.2$

[SL, Schmauch, en préparation]

Inverted hierarchy case



$\lambda_H = 0.2$

→ inverted hierarchy disfavoured

[SL, Schmauch, en préparation]

An low-scale scenario: ARS leptogenesis

A lepton asymmetry can be produced via CP-violating oscillations of GeV-scale (M < 100 GeV) Majorana neutrinos, rather than in the decays of heavy neutrinos (ARS mechanism) [Akhmedov, Rubakov, Smirnov '98]

The SM neutrino masses are still produced via the seesaw mechanism, but the explanation of their smallness is lost

This is how the BAU is produced in Shaposhnikov's model, where N_1 is a keV sterile neutrino that constitutes dark matter, and N_2 and N_3 produce a lepton asymmetry in their oscillations [Asaka, Shaposhnikov '05]

It is not clear however whether the observed baryon asymmetry can be reproduced in this model

ARS leptogenesis with 3 GeV-scale Majorana neutrinos can work!

Works in particular for large active-sterile neutrino mixing angles, which can be probed at the LHC [A. Abada et al. '18]

Conclusions

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

To explain its origin, new physics beyond the Standard Model must be invoked. Leptogenesis, which relates neutrino masses to the baryon asymmetry, is a very interesting possibility.

Although difficult to test, leptogenesis would gain support from:

- observation of neutrinoless double beta decay: $(A,Z) \to (A,Z+2)\ e^- e^-$ [proof of the Majorana nature of neutrinos - necessary condition]
- observation of CP violation in the lepton sector, e.g. in neutrino oscillations [necessary but not sufficient]
- non-observation of other light scalars (which are present in many non-standard electroweak baryogenesis scenarios) than the Higgs boson at high-energy colliders; strong constraints on additional CP violation (e.g. EDMs)

Back-up slides

A popular book on neutrinos (in French)

(apologies for the self-promotion)

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

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

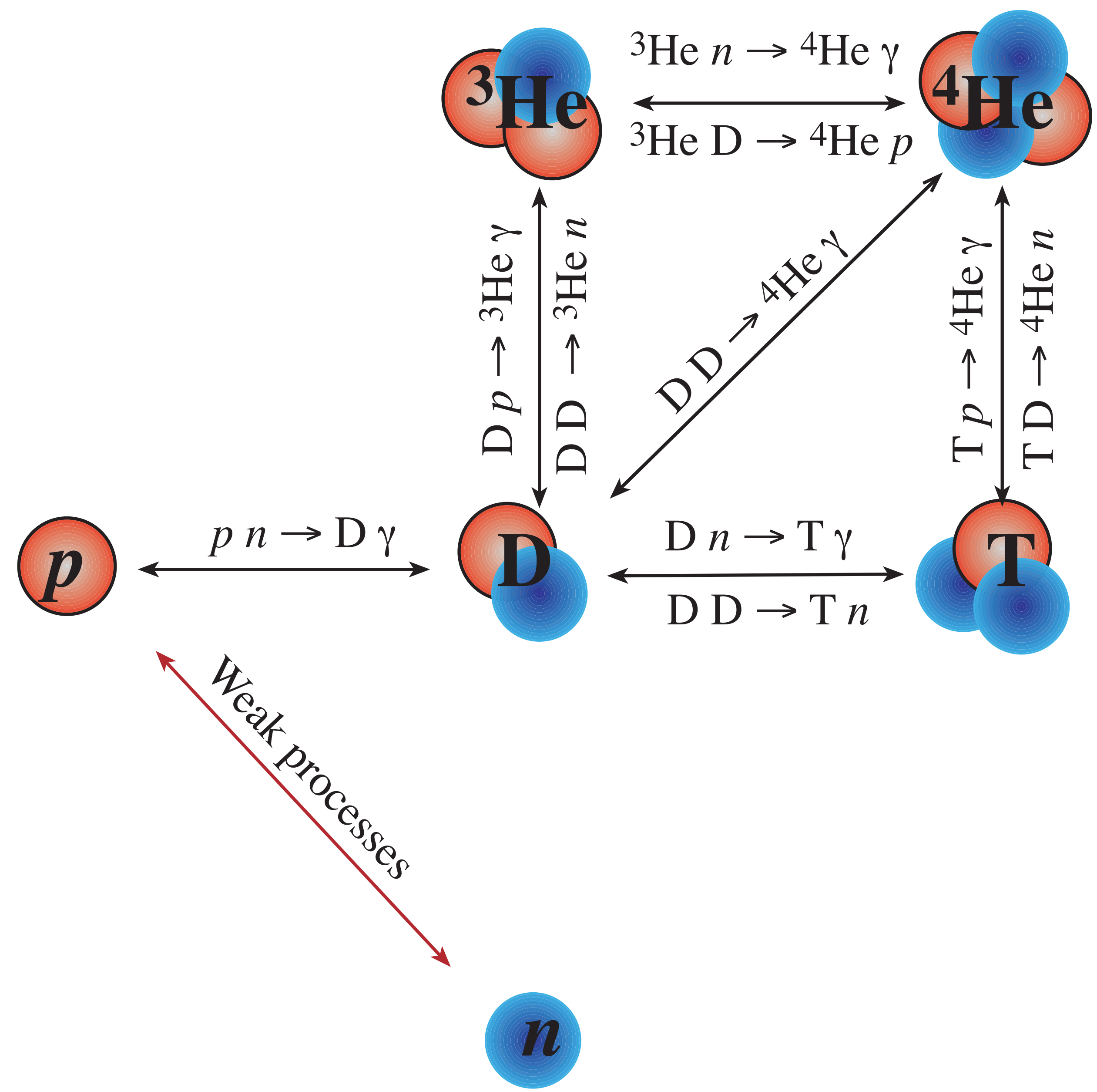
* clusters of galaxies: would observe strong γ-ray emission from matter-antimatter annihilations, such as $p + \bar{p} \rightarrow \pi^0 + X \rightarrow \gamma\gamma + X$

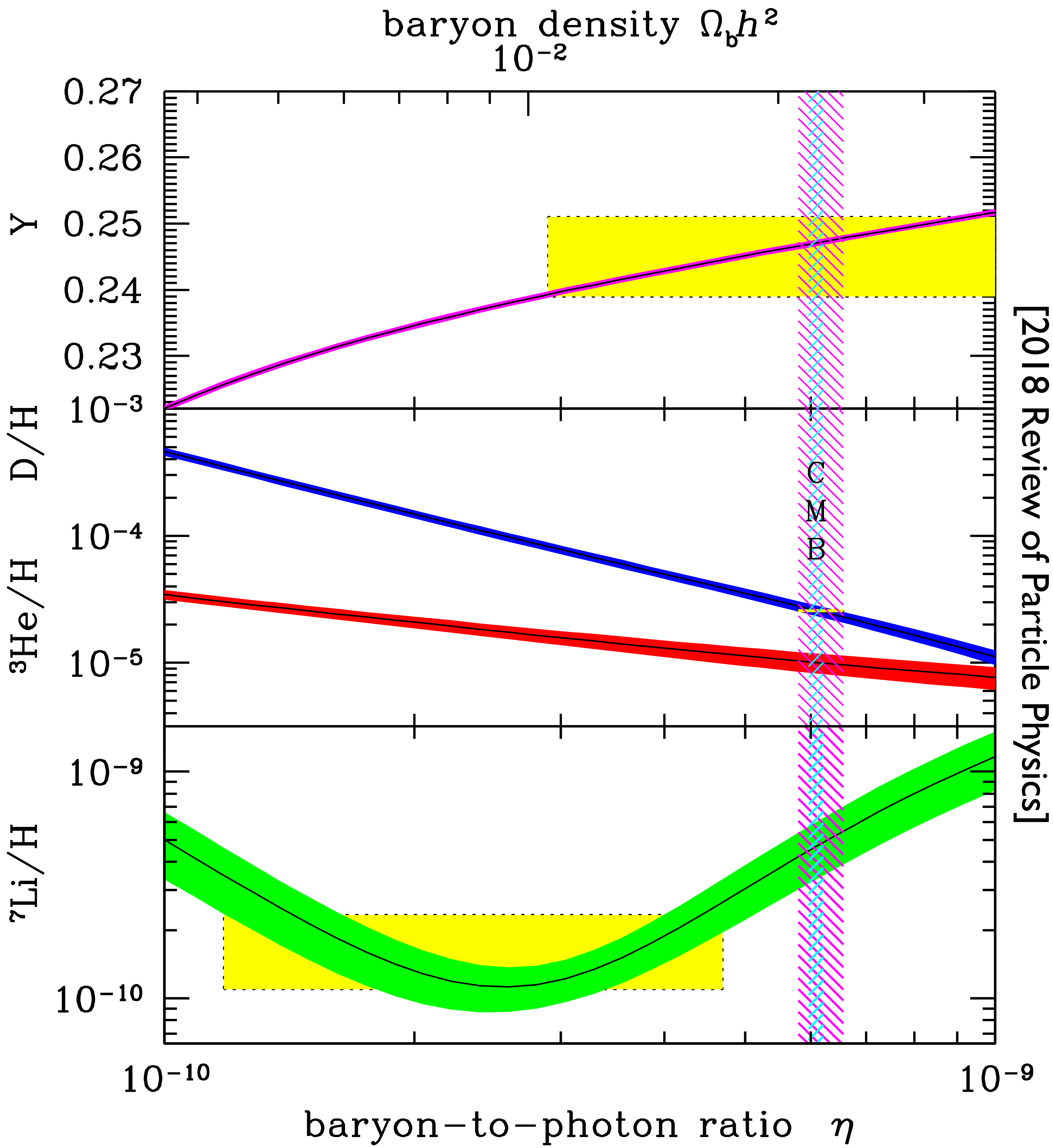
Could there be matter/antimatter separation over larger scales?

Would require violation of causality (the causal horizon before annihilation freeze-out contained only a tiny fraction of our visible Universe) in a non-inflationary Universe. Also problematic if inflation

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

The abundances of D and ^{3}He are very sensitive to η, since a larger η accelerates the synthesis of D and ^{3}He, which are themselves needed for the synthesis of ^{4}He, resulting in final lower abundances for D and ^{3}He





There is a range of values for η consistent with all observed abundances ("concordance", up to a factor of 2 for Li)
→ major success of Big Bang cosmology

$$\eta = (5.8 - 6.6) \times 10^{-10}$$
$$(95\%\ \text{C.L.})$$

- curves = BBN prediction (95% C.L.)
- boxes = observed abundances

The cosmic microwave background (CMB) is a remnant of the era of last scattering (of the photons off electrons), after the recombination epoch (p + e- $\rightarrow$ H atoms), where the Universe became transparent to photons

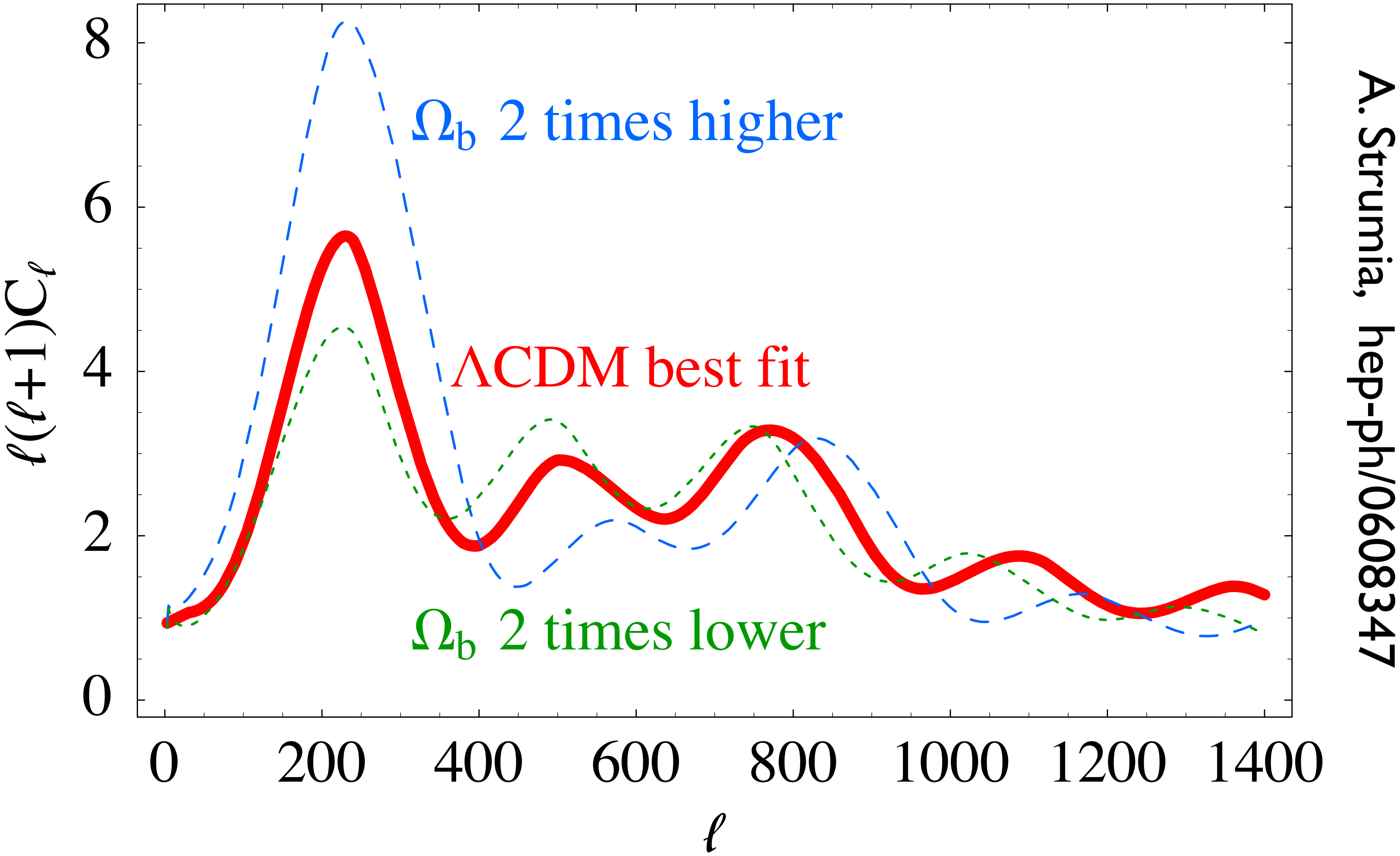
$\Rightarrow$ blackbody spectrum with T = 2.725 K and small ($\delta T/T \sim 10^{-5}$) temperature anisotropies

Most of the cosmological information contained in the anisotropies can be extracted from the temperature 2-point function. The latter is studied by expanding the temperature distribution on the sky in spherical harmonics, then computing the variance of the coefficients a_{lm} :

$$\frac{\delta T}{T}(\theta, \phi) \ = \ \sum_{l=1}^{\infty} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\theta, \phi)$$

$$\langle a_{lm} a^*_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}$$

The C_l are then plotted as a function of the multipole l



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

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

$$\Rightarrow \quad \eta = (6.13 \pm 0.08) \times 10^{-10}$$ (Planck 2018, 95% C.L.)

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]

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

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]

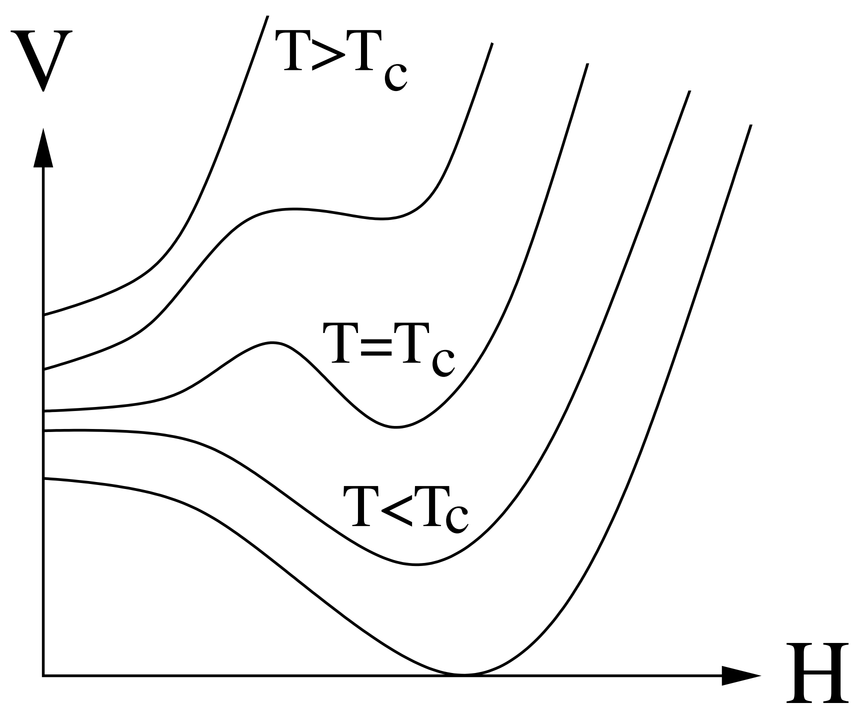
For the mechanism to work, it is crucial that sphalerons are suppressed inside the bubbles (otherwise will erase the generated B asymmetry)

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

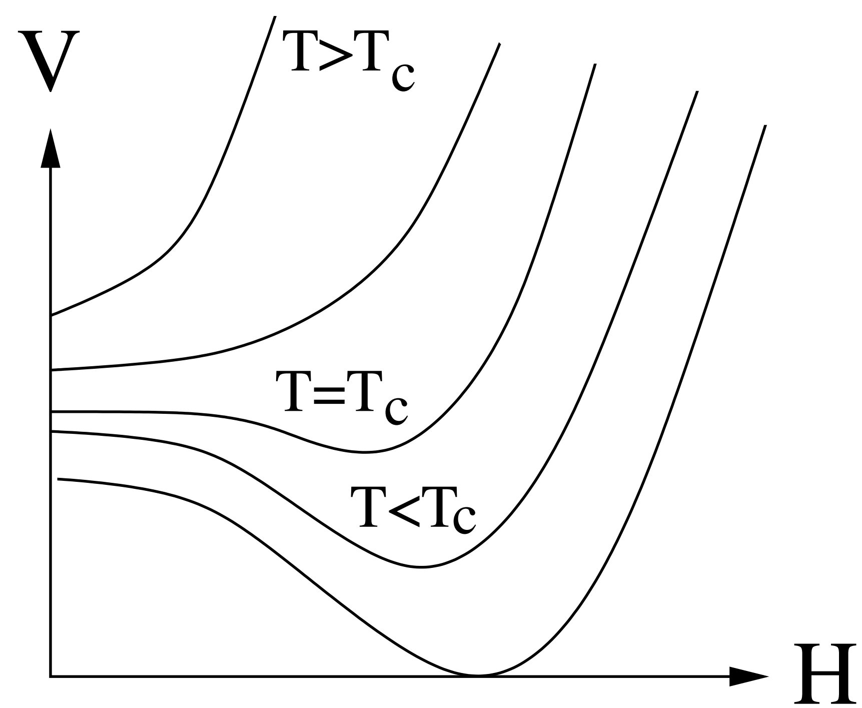
The out-of-equilibrium condition is $\dfrac{\langle\phi(T_c)\rangle}{T_c} \gtrsim 1$

$\Rightarrow$ 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



first order



second order

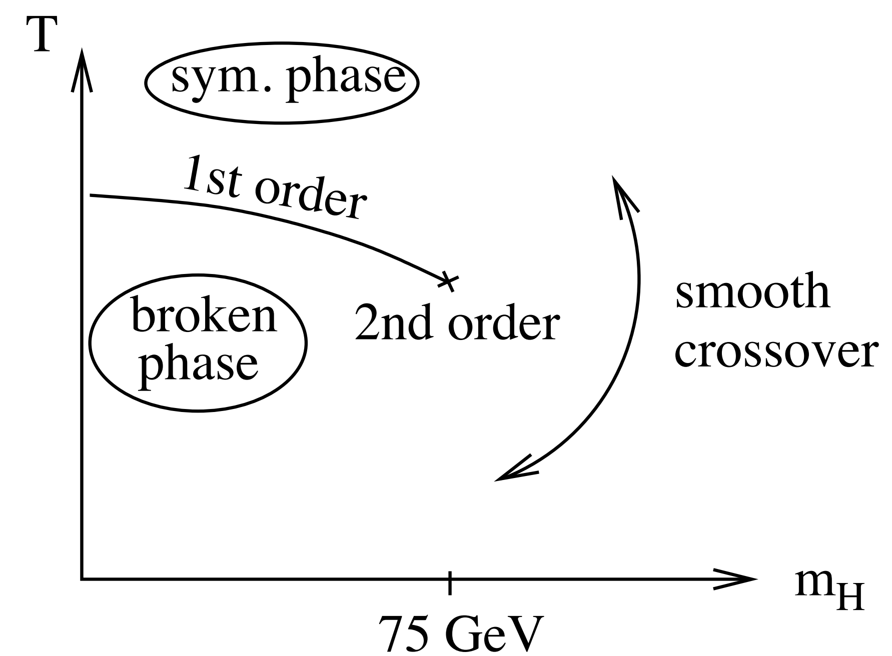
One obtains $\phi(T_c) \propto v^2 T_c / m_H^2$

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

$\Rightarrow$ excluded by the LHC, which measured $m_H = 125\,\mathrm{GeV}$

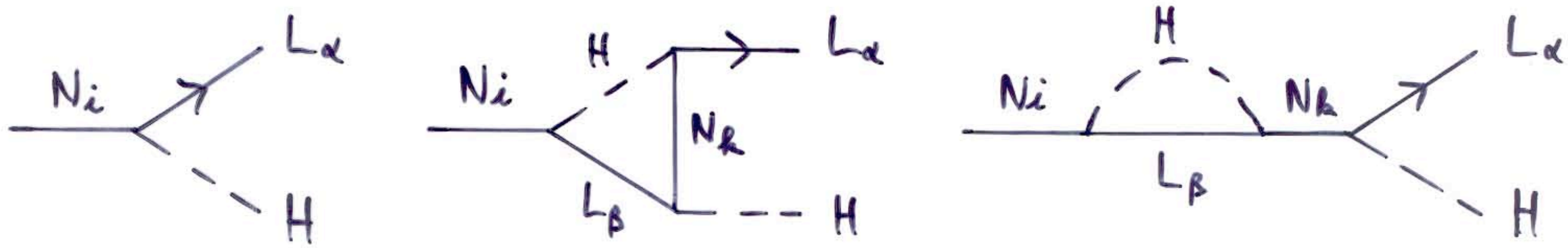
Kajantie et al.
(hep-ph/9605228)



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

CP asymmetry due to interference between tree and 1-loop diagrams:



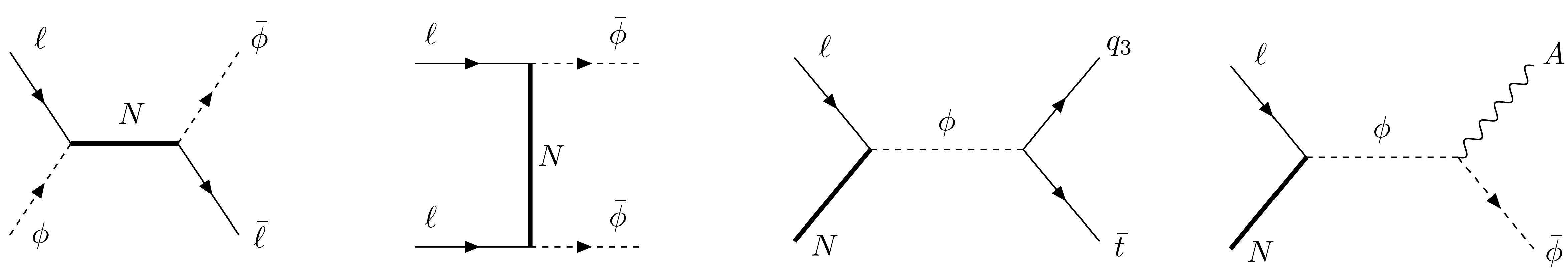
$$\Rightarrow \quad \Gamma(N_i \to LH) \neq \Gamma(N_i \to \bar{L}H^\star)$$

Covi, Roulet, Vissani '96
Buchmüller, Plümacher '98

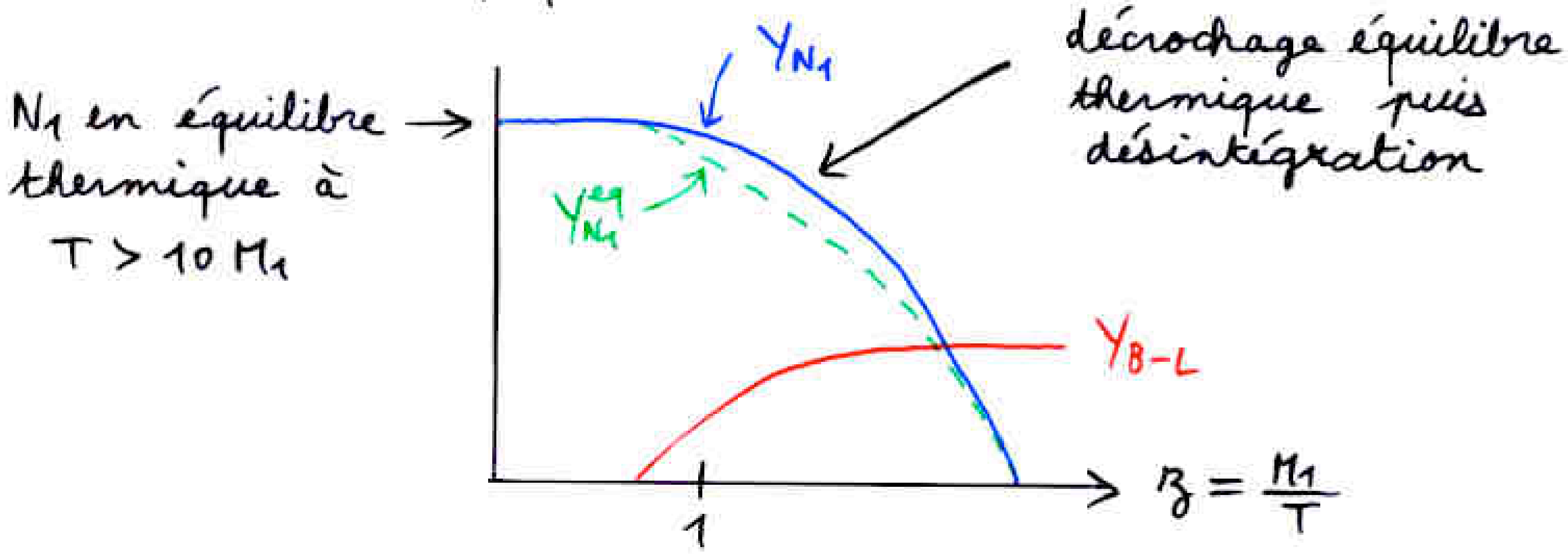
CP asymmetry in N1 decays (hierarchical case $M_1 \ll M_2, M_3$) ⇒ generation of a lepton asymmetry proportional to $\epsilon_{N_1} \equiv \dfrac{\Gamma(N_1 \to LH) - \Gamma(N_1 \to \bar{L}H^\star)}{\Gamma(N_1 \to LH) + \Gamma(N_1 \to \bar{L}H^\star)}$

The generated asymmetry is partly washed out by L-violating processes:

- inverse decays $LH \to N_1$
- ΔL=2 N-mediated scatterings $LH \to \bar{L}\bar{H}\,, \quad LL \to \bar{H}\bar{H}$
- ΔL=1 scatterings involving the top or gauge bosons



évolution typique :



Can leptogenesis explain the observed baryon asymmetry?

⇒ must compare Y_B computed from leptogenesis with observed value

- η essentially depends on M_1 and on $\tilde{m}_1 \equiv (YY^\dagger)_{11} v^2 / M_1$, which controls the out-of-equ. decay condition / strength of washout processes:

$$\Gamma_{N_1} < H(T = M_1) \quad \Longleftrightarrow \quad \tilde{m}_1 < \tilde{m}_1^\star = 2.2 \times 10^{-3}\,\mathrm{eV}$$

- ϵ_{N_1} depends on the N_i masses and couplings, but is bounded by a simple function of M_1, m_1, m_3 and $\tilde{m}_1$ [case $M_1 \ll M_2, M_3$]:

$$|\epsilon_{N_1}| \leq \frac{3}{16\pi} \frac{M_1 (m_3 - m_1)}{v^2} f\left(\frac{m_1}{\tilde{m}_1}\right) \qquad 0 \leq f\left(\frac{m_1}{\tilde{m}_1}\right) \leq 1$$

Davidson, Ibarra
Hambye et al.

Lepton flavour effects in scalar triplet leptogenesis

The lepton asymmetry is the sum of the asymmetries stored in each lepton flavour (e, μ, τ) $\Rightarrow$ coupled evolution of the different flavour asymmetries

The proper description of flavour effects involves a 3x3 matrix in flavour space:

$(\Delta_\ell)_{\alpha\beta}$
- diagonal entries = flavour asymmetries $\Delta_{\ell_\alpha} \equiv Y_{\ell_\alpha} - Y_{\bar{\ell}_\alpha}$
- off-diagonal entries = quantum correlations between flavours

Boltzmann equation for $(\Delta_\ell)_{\alpha\beta}$:

$$sHz\frac{d(\Delta_\ell)_{\alpha\beta}}{dz} = \left(\frac{\Sigma_\Delta}{\Sigma_\Delta^{\rm eq}} - 1\right)\gamma_D\, \mathcal{E}_{\alpha\beta} - \underbrace{\mathcal{W}^D_{\alpha\beta} - \mathcal{W}^{\ell H}_{\alpha\beta} - \mathcal{W}^{4\ell}_{\alpha\beta} - \mathcal{W}^{\ell\Delta}_{\alpha\beta}}_{\text{washout terms}}$$

CP-asymmetry matrix

All terms on the RHS of the Boltzmann equation for $(\Delta_\ell)_{\alpha\beta}$ transform covariantly under $\ell \to U\ell$:

$$\mathcal{M} \to U^* \mathcal{M} U^T \qquad \mathcal{M} = \{\mathcal{E}, \mathcal{W}^D, \mathcal{W}^{\ell H}, \mathcal{W}^{4\ell}, \mathcal{W}^{\ell\Delta}\}$$

Correlation between different flavour asymmetries play an important role in scalar triplet leptogenesis

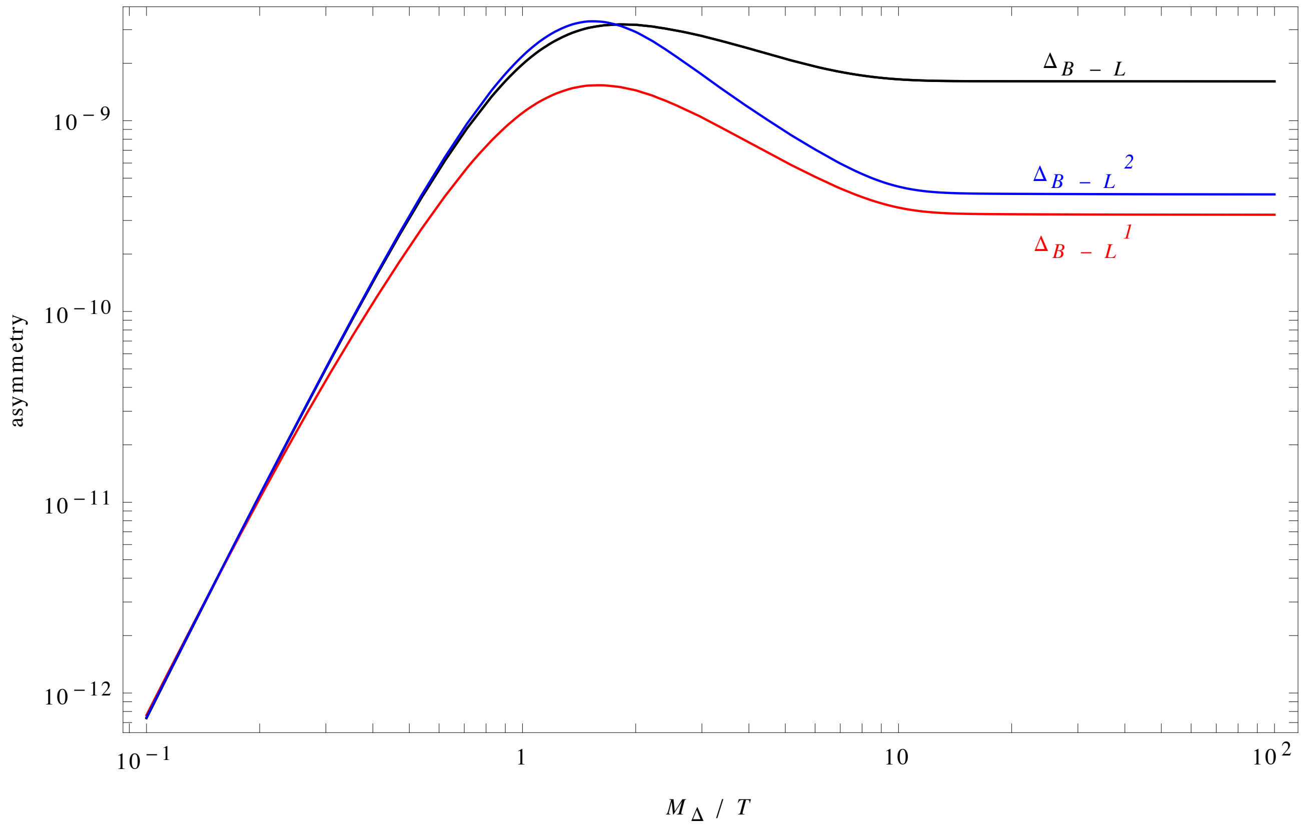
Generated baryon asymmetry computed in three different ways: flavour-covariant computation with the matrix of flavour asymmetries; Boltzmann equations for individual flavour asymmetries (results depend on the basis choice: neutrino vs charged lepton mass eigenstates)

matrix of flavour asymmetries

neutrino mass eigenstate basis

charged lepton eigenstate basis

$$(M_\Delta = 5 \times 10^{12}\,\mathrm{GeV})$$



[SL, Schmauch '15]

First hints of CP violation at T2K

Long baseline accelerator experiment in Japan (295 km)

Observes a stronger asymmetry between the antineutrino $(\bar{\nu}_\mu \to \bar{\nu}_e)$ and the neutrino mode $(\nu_\mu \to \nu_e)$ than expected $\Rightarrow$ suggests CP violation (CP conservation excluded at 2σ), with a preferred value $\delta \approx 3\pi/2$

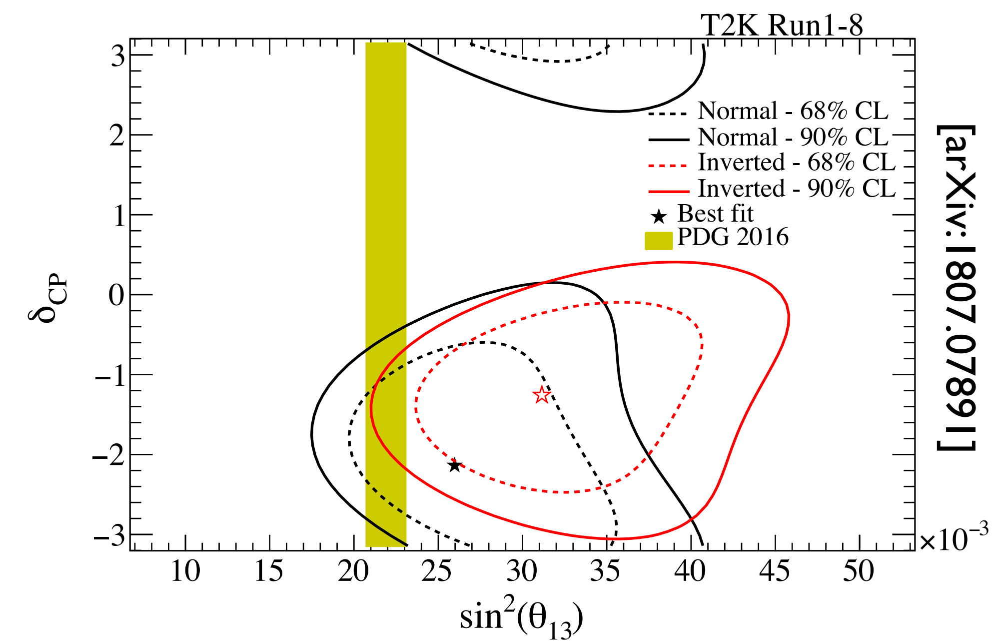
T2K 2010-2016

Normal	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν mode	28.7	24.2	19.6	24.1	32
$\bar{\nu}$ mode	6.0	6.9	7.7	6.8	4

Inverted	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν mode	25.4	21.3	17.1	21.3	32
$\bar{\nu}$ mode	6.5	7.4	8.4	7.4	4

[Phys. Rev. Lett. 118 (2017) 151801]

T2K 2010-2017



[arXiv:1807.07891]

FIG. 5. The 68% (90%) constant $-2\Delta\ln\mathcal{L}$ confidence regions in the $\sin^2\theta_{13}$-δ_{CP} plane using a flat prior on $\sin^2(2\theta_{13})$, assuming normal (black) and inverted (red) mass ordering. The 68% confidence region from reactor experiments on $\sin^2\theta_{13}$ is shown by the yellow vertical band.

How to account for neutrino masses?

Simplest possibility: add a RH neutrino to the SM

In addition to the Dirac mass term $-m_D\,\bar{\nu}_L N_R + \text{h.c.}$, must write a Majorana mass term for the RH neutrino, which is allowed by all (non-accidental) symmetries of the SM (or justify its absence):

$$-\frac{1}{2}\,M\,\bar{N}^c_L N_R + \text{h.c.} \;=\; -\frac{1}{2}\,M\,N^T_R C N_R + \text{h.c.} \qquad \Delta L = 2 \qquad \Delta T^3 = 0$$

[only lepton number, if imposed, can forbid this term]

<u>Mass eigenstates</u> : write the mass terms in a matrix form and diagonalize

$$\begin{aligned}
\mathcal{L}_{\text{mass}} &= -\frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \bar{N}^c_L\end{pmatrix}\begin{pmatrix}0 & m_D\\ m_D & M\end{pmatrix}\begin{pmatrix}\nu^c_R\\ N_R\end{pmatrix} + \text{h.c.}\\
&= -\frac{1}{2}\begin{pmatrix}\bar{\nu}_{L1} & \bar{\nu}_{L2}\end{pmatrix}\begin{pmatrix}m_1 & 0\\ 0 & m_2\end{pmatrix}\begin{pmatrix}\nu^c_{R1}\\ \nu^c_{R2}\end{pmatrix} + \text{h.c.}
\end{aligned}$$

where $\left\{\begin{aligned}\nu_{L1} &= \cos\theta\,\nu_L - \sin\theta\,N^c_L\\ \nu_{L2} &= \sin\theta\,\nu_L + \cos\theta\,N^c_L\end{aligned}\right.$

Defining $\nu_{Mi} \equiv \nu_{Li} + \nu^c_{Ri}$ (such that $\nu_{Mi} = \nu^c_{Mi}$), one can see that the mass eigenstates are 2 Majorana neutrinos with masses m1 and m2 :

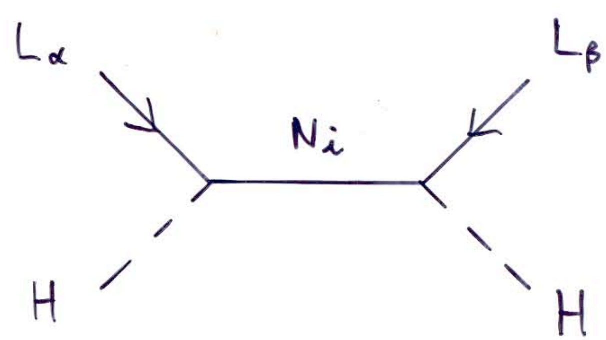
$$\mathcal{L}_{\rm mass} = -\frac{1}{2}\sum_{i=1,2} m_i\,\bar\nu_{Li}\nu^c_{Ri} + \text{h.c.} = -\frac{1}{2}\sum_{i=1,2} m_i\,\bar\nu_{Mi}\nu_{Mi}$$

"Seesaw" limit : $M \gg M_W \gtrsim m_D$

(N_R = gauge singlet ⇒ M unconstrained by electroweak symmetry breaking)

$$m_1 \simeq -m_D^2/M \ll M_W \qquad m_2 \simeq M \gg M_W$$

$$\sin\theta \simeq \frac{m_D}{M} \ll 1 \quad \Rightarrow \quad \nu_{L1} \simeq \nu_L\,, \quad \nu^c_{R2} \simeq N_R$$



→ the light Majorana neutrino is essentially the SM neutrino

→ natural explanation of the smallness of neutrino masses

New physics interpretation : M = characteristic scale of the new physics responsible for lepton number violation – might be related to Grand Unification: the fermion content of SO(10) includes a RH neutrino in addition to the SM fermions, and B-L is a generator of SO(10)